MOLYBDENUM

A MATERIALS SURVEY

BY WILMER McINNIS

* * * * * * * * * * Information Circular 7784

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OFFICE OF THE DIRECTOR

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON 25, D. C.

December 26, 1956

Hon. Arthur S. Flemming
Director
Office of Defense Mobilization
New GAO Building
Washington 25, D. C.

My dear Mr. Flemming:

Copies of the Materials Survey - Molybdenum, prepared by the Bureau of Mines with the cooperation of the Geological Survey for the Office of Defense Mobilization, are being forwarded to your office.

This report is the first Materials Survey to be completed under the terms of the April 15, 1955, agreement between the Department of the Interior and the Office of Defense Mobilization which assigned responsibility to Interior for preparation and revision of Surveys covering 45 mineral commodities. The Molybdenum report is the thirteenth Materials Survey published by the Bureau of Mines, the others having been prepared under an agreement made in 1950 with the National Security Resources Board.

Manuscript revisions proposed by reviewing officials of the Office of Defense Mobilization have been incorporated in the Survey.

Sincerely yours,

Marling J. Ankeny

Director

III

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Foreword

Materials Surveys are designed to bring into a single document all the fundamental data needed by war or defense personnel with major responsibilities with respect to the Survey subjects. The Surveys dealing with metals and minerals summarize the demand-supply position in the United States and include information on production, imports, consumption, exports, capacity, interchangeability, substitutes, possibilities for expansion and pertinent history, usually in some detail back to 1925. The properties of the commodity and its principal compounds and alloys are described. Exploration, mining, and metallurgical methods are discussed. Domestic and foreign resources and reserves are covered. An extended presentation of the structure of the industry, including major corporations, transportation service, processing facilities, interrelationships to other industries, pertinent laws and taxation policies, tariffs, Government controls, special labor problems, and history of wartime control experiences, are included. Other special data are presented for particular commodities.

In undertaking Surveys, precedence is given to commodities of highest priority in defense urgency. Molybdenum is one of the most important ferroalloying metals and essential to the Nation's defense industries.

The Molybdenum Materials Survey was prepared in the Division of Minerals under the direct supervision of Henry G. Iverson, Chief, Branch of Ferrous Metals and Ferroalloys, and Norwood B. Melcher, former Chief of that Branch. The manuscript was reviewed, in whole or in part, by specialists in the Bureau of Mines, Geological Survey, and industry. Special acknowledgment is made of substantial contributions to the report by Climax Molybdenum Co., Kennecott Copper Corp., Molybdenum Corporation of America, and Molybdenite Corporation of Canada, Ltd.

CHARLES W. MERRILL,
Chief, Division of Minerals.

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MOLYBDENUM[1]

A MATERIALS SURVEY

BY

WILMER McINNIS[2]

WITH A CHAPTER ON GEOLOGY AND RESOURCES BY S. C. CREASEY

Introduction and Summary

MOLYBDENUM, one of the more versatile alloying elements in modern metallurgy, was first isolated by Hjelm in 1782. The pure metal is silvery white and softer than steel. It melts at a higher temperature than all other metals except rhenium, tungsten, and tantalum. Molybdenum, a member of group V of the periodic table, chemically exhibits valences in stable compounds of 2, 3, 4, 5, and 6. It is a strong carbide-forming element, and much of its alloying effect in steel is imparted through the formation of carbides.

Molybdenum occurs in nature only in combination with other elements. The most common occurence is molybdenite (MoS_2), which is widely distributed throughout the world; the few known commercial deposits are the major sources of molybdenum. The other commercially important mineral, wulfenite ($PbMoO_4$), was a major source of molybdenum in the United States during the early part of the 20th century, but with exploration and development of the world-famous Climax molybdenite deposit during the World War of 1914–18, molybdenite soon became the world's major source of molybdenum. In recent years, virtually no wulfenite has been mined. Many copper deposits contain minute percentages of molybdenite; and, since the inauguration during the early 1930's of the recovery of molybdenite as a byproduct of these deposits, they have been an important source of molybdenum.

Methods of mining molybdenum depend largely upon the type of deposit. In porphyry-type deposits large-scale caving methods are employed, but in vein-type deposits cut-and-fill stoping is preferred. Molybdenum ores require concentration before useful products can be made. Flotation is universally employed in concentrating molybdenite.

Except for that added direct to steel and that used in the manufacture of lubricants, molybdenite concentrates are roasted to molybdic oxide (MoO_3). The molybdic oxide is both a raw material for the manufacture of other molybdenum products and a product for direct consumption as an alloying element. Hydrogen reduction is the preferred method for producing metallic molybdenum. Ferromolybdenum is produced by the electric furnace and the thermite processes. Other products are produced either by metallurgical or chemical processes.

The first recorded commercial production of molybdenum was in Norway during the last quarter of the 19th century, and by 1900 both Australia and the United States had small outputs. During the first quarter of the 20th century the United States took the lead in molybdenum production; and, since reopening of the Climax mine in 1924, has been the world's major source, producing 92 percent of estimated output in 1955. Known ore reserves indicate that the United States will continue to be the major supplier for many years to come.

An estimated 85 to 90 percent of all molybdenum consumed in recent years was used in ferrous alloys, and the remainder was consumed in metallic form, in nonferrous alloys, and in nonmetallurgical uses.

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[1] Work on manuscript completed September 1956.

[2] Commodity specialist, Bureau of Mines.

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HISTORY

DISCOVERY AND EARLY RESEARCH

Centuries ago the Greeks and Romans used the term "molybdos" or "molybditis" to describe minerals that were soft and "leadlike" in character. The terms were probably applied to the minerals now known as galena, graphite, and molybdenite. At a still later period, the word "molybdaena" was applied to graphite and the mineral molybdenite. In 1778, Karl Wilhelm Scheele, the celebrated Swedish chemist, demonstrated that molybdenite, unlike graphite on treatment with nitric acid produced a "peculiar white earth" with acidic properties; he assigned the name "molybdic acid" to this substance. He also found that when the mineral was heated, sulfurous fumes were given off, and he concluded that molybdenite was a sulfide of molybdenum. Four years later (1782) J. J. Hjelm isolated the metal itself, which proved to be the new element, molybdenum.

In 1893 the German chemists Sternberg and Deutsch produced a 96-percent-pure metal by reducing molybdate of lime with carbon and then separating the lime with hydrochloric acid. The impure metal was reported to have been used in experiments in an effort to utilize the metal in tool steel in place of tungsten. In 1894 the metal was first obtained by means of the electric furnace, but the high carbon content (9 percent) made it unsatisfactory for use. In the same year, Schneider & Co. produced molybdenum-bearing armorplate at its Creusot works in France. This was the first recorded report on the use of molybdenum as an alloying element in steel. A short time later, Henri Mossian, a French chemist, made extensive experiments in the reduction of molybdenum by means of the electric furnace and succeeded in obtaining 99.98-percent-pure metal. Mossian then devoted a considerable amount of study to its physical and chemical properties. He established its atomic weight and determined many other of its now known qualities. These experiments and results were successful enough to cause the metal to be considered commercially important for the first time.

EARLY PRODUCTION AND USES

The first production of molybdenite was probably from the Knaben mine in the Knaben-Flekkefjord district, southern Norway, near the end of the 18th or the beginning of the 19th century. Its uses were evidently unimportant and small, for the mine had no important production until research during the last quarter of the 19th century stimulated interest in the mineral enough to cause it to be reopened about 1880; however, production was irregular and small until just before the end of the century, by which time the United States and Australia were also producing small quantities, but production in the United States was discontinued in 1905 and was not resumed until 1914.

Although molybdenum had previous commercial applications in certain chemicals and dyes, the first record of its commercial use as an alloying element in steel was said to be in 1898, when the Sanderson Steel Co. began to market a molybdenum self-hardening tool steel, but production of the steel was discontinued before 1905. This use greatly stimulated interest in the metal as an alloying element, and metallurgists devoted considerable study to its use as an alloying element in high-speed steel. However, tools made from the molybdenum high-speed steels gave erratic performance, owing largely to lack of knowledge of the critical heat-treating range subsequently developed and demonstrated at Watertown Arsenal in 1930. This early failure gave molybdenum a bad reputation in the United States, and for the next decade there was very little development in the United States on the use of the metal as an alloying element.

In 1907 Fink (*3*)[3] produced ductile molybdenum by compressing the hydrogen-reduced powder into bars that were then heated and hammered into rod or sheet. A few years later the metal was being produced in ductile form for commercial use.

The difficulty of separating the mineral molybdenite from its ores was the subject of much study during the early years of the 20th century. Frank E. Elmore, one of the pioneers of oil flotation, devised the Elmore vacuum process, based on liberation of dissolved air and gases by means of reduction of pressure, which enabled the bubbles to lift quite large masses of oil-coated minerals. This vacuum process was installed in several molybdenite mills in Norway, the first being at the Kvina mine in 1913; this was probably the beginning of oil flotation of molybdenite. Later research

[3] Italicized figures in parentheses refer to items in the bibliography, which are listed by years.

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demonstrated that molybdenite was readily amenable to vastly improved flotation methods now universally practiced for concentrating the mineral from its ores.

WORLD WAR I

At the outbreak of World War I total annual production of molybdenum was at a rate of about 200,000 pounds. Demand for the new alloying element, both as a substitute for tungsten and for use in new alloys, during the war caused a temporary shortage in supply. Because of the supply condition the British admiralty commandeered the entire molybdenum output of British-controlled territory early in the war, and in 1917 the British Government contracted for the entire output of Norwegian molybdenite mines.

Early in the war a wide search for new molybdenum deposits got underway in the United States. Small wulfenite mines in Arizona were reopened, and in 1917 Climax Molybdenum Co., and Molybdenum Products Corp. began active exploration on different parts of the same large molybdenite deposit in Lake County, Colo., while the Primas Chemical Co. was developing the molybdenite deposit at Camp Urad in Clear Creek County, Colo. Active exploration and development work were also being carried out in several other countries, including Canada. The Moss mine, situated 3 miles north of Quyon Station, Quebec, Canada, began producing molybdenite in 1916 and soon thereafter became the world's leading producer for a brief time (*9*). These developments led to total world production of about 5 million pounds during 1914–18, with an annual high of 1.8 million pounds in 1918; over 850,000 pounds was produced in the United States.

PEACETIME DEVELOPMENTS

The close of World War I left large inventories of ferromolybdenum in the hands of United States consumers who had accumulated the stocks in anticipation of military projects, such as the Liberty engines and "baby" tanks which never reached volume production, and large stocks were probably held by foreign consumers also. These large stocks, along with stocks at United States mines, were more than ample to meet the small demand for peacetime uses; as a result, the United States molybdenum industry collapsed, production ceasing completely in 1920. Canada and Norway also ceased production in 1920, but Australia continued to produce in a small way.

A campaign launched in the early 1920's to develop peacetime applications for molybdenum soon began to show results. In the summer of 1920 molybdenum-bearing alloy steel was used in Studebaker automobiles. The use of molybdenum alloy steels by the automotive industry increased rapidly thereafter, and before the end of 1925 the chromium-molybdenum steels (SAE 41000 series) had been accepted by the Society of Automotive Engineers.

The Questa mine, in Taos County, N. Mex., was reopened in 1923, and production from the Climax mine in Lake County, Colo., was resumed in 1924. The reopening of these mines assured a steady supply of molybdenum to meet the rapidly expanding peacetime uses. In 1925 United States production exceeded 1 million pounds of molybdenum for the first time and represented over two-thirds of total world production in that year.

As molybdenum had gained recognition by the steelmakers as a cheap and effective alloying element for many alloys, it was soon accepted by foundries for addition to alloy cast iron.

In 1930 Watertown Arsenal studied molybdenum high-speed steels and determined the proper temperature ranges for forging and heat treating. In the following year molybdenum high-speed steels were marketed in the United States, but their acceptance for peacetime uses was gradual.

By the early 1930's United States production of molybdenum was more than ample to meet domestic needs; and a large part was exported, mostly to Europe. Although export figures are not available, Bureau of Mines estimates indicate that about 50 percent of the United States production during the 1930's were exported.

In 1933 the Greene Cananea Copper Co., Cananea, Sonora, Mexico, inaugurated recovery of molybdenite as a byproduct from its copper-mining operations, and for the next several years Mexico ranked as the world's second largest producer of molybdenum. Three years later the Kennecott Copper Corp. began recovering molybdenite as a byproduct from its copper-mining operations at Bingham, Utah. Byproduct recovery of molybdenite was installed later at other Kennecott Copper Corp. copper mines and by other producers of copper and tungsten, including the Braden Copper Co. at Sewell, Chile, which has since made that country the second largest producer of molybdenum.

WORLD WAR II

Although world production of molybdenum had increased to an annual rate of over 34 million pounds by the start of World War II in September 1939, it was not enough to meet increased demands brought about by events of the war. The severe shortage of chromium, nickel, tungsten, and vanadium that developed early in the war made it necessary to use sub-

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stitutes wherever practical. Metallurgists, having gained considerable experience with molybdenum during the 1930's, were quick to recognize its versatility as an alloying element and developed many new alloys containing the metal as well as substituting it in part for tungsten in high-speed steel. The defense requirements, plus essential civilian uses for molybdenum, soon became greater than mining and milling capacity, which led to a critically short supply that was somewhat alleviated by selective mining at the Climax mine, Colorado, where some 23 million tons of ore had already been blocked out, and by increased output from byproduct sources and other small molybdenum mines. Maximum output during the war was reached in 1943, when the United States molybdenum production—about 90 percent of total world output—was almost 61.7 million pounds, of which 75 percent was from the Climax mine.

Export and use controls were measures taken by the United States during the war to conserve the supply of molybdenum. Export controls inaugurated in July 1940 required individual licensing of molybdenum, after approval by an Interdepartmental Foreign Requirements Committee, for shipments to friendly countries to meet essential requirements. Domestic use controls imposed in the following year were aimed at preventing the buildup of inventories to unnecessary levels at consumers' plants.

Although industry had been slow to accept molybdenum-type high-speed steels for peacetime use, they were widely accepted during the war, and their use represented a large percentage of the molybdenum consumed. Over 119 million pounds of molybdenum contained in products was consumed in the United States during the war years 1942–44. It was predominantly employed as an alloying element in iron and steel; but a relatively small quantity was consumed in electrical equipment, special heat- and corrosion-resistant alloys, lithographing and printing inks, and chemical reagents, as well as in other minor applications.

The occupation of Norway gave Germany possession of the Knaben mine, which cut off this source of molybdenum to the Allies. As a result of this and increased demand, United States exports increased substantially, reaching a wartime peak of over 11 million pounds in 1942; over 6 million pounds of this was exported to the U. S. S. R. During this period all of Chile's production of molybdenum was exported to the United States, and Canada's production was shipped to the United States for conversion and reshipment.

POST WORLD WAR II

The United States molybdenum industry went into a slump just following the cessation of hostilities of World War II. This slump was due largely to slackened demand, while industry was reconverting plants back to peacetime production and to the salvage of high-alloy battle scrap, which reduced the need for newly mined molybdenum. As a result of this decreased demand, Climax Molybdenum Co. converted part of its molybdenum plant at Climax, Colo., to byproduct production of tungsten, tin, and pyrite and reduced its ore-milling capacity from about 20,000 to around 14,000 tons a day. Meanwhile, the Mammoth-St. Anthony and Urad mines were closed. United States production of 18.2 million pounds in 1946 was the lowest in a decade.

Development of the jet engine, which brought a need for alloys that could withstand the high operating temperatures, directed the attention of researchers to molybdenum; but its inability to withstand oxidation in air at high operating temperatures greatly restricted its use in these alloys. However, molybdenum-type high-speed and low-alloy steels developed during the war were accepted by industry for peacetime uses, and demand for the metal continued to increase.

Following the outbreak of the Korean War in mid-1950, the molybdenum supply became critical. Late in that year molybdenum was included on the National Strategic Stockpile list of critical and strategic materials. Production was expanded to the limit of existing mine and mill facilities, and construction and development programs to expand production further were instigated. To stimulate the production of molybdenum, the United States Government entered into a long-term contract with Climax Molybdenum Co. late in 1950. The contract was modified the following year, calling for still greater output. Later Climax Molybdenum Co. obtained another Government contract that called for the recovery of molybdenum from low-grade ores. At a result of these contracts, the company subsequently increased milling capacity to about 28,000 tons of ore a day, and another addition in 1956 increased capacity to 32,000 tons a day.

Several domestic use orders, designed to conserve molybdenum and provide control of its distribution, were issued in 1951. The International Materials Conference Committee on Molybdenum and Tungsten began issuing allotments of molybdenum in the third quarter of 1951. These international and domestic use controls were abandoned later when the supply of molybdenum became adequate to meet demand. In 1952 the United States Government announced a molybdenum-expansion goal of 58 million pounds of domestically produced molybdenum. The expansion goal was revised upward in the same year to 70 million pounds of domestically produced molybdenum in 1954.

The Molybdenite Corp. of Canada, Ltd., re-

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opened its La Corne mine in 1951 and in 1953 negotiated a contract with the United States Government for the supply of 6 million pounds of molybdenite at over the then prevailing market price.

Although United States production of molybdenum in 1955 was almost 61.8 million pounds—the highest in any year—the supply was tight during the last part of the year. However, new byproduct recovery of molybdenum by San Manuel Copper Corp. and by American Smelting & Refining Co. from its copper mines in Arizona, begun in 1956, and planned byproduct recovery by The Anaconda Co. from its copper mines in Chile are expected to increase world output materially.

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GEOLOGY AND RESOURCES

By S. C. Creasey[4]

SUMMARY OF RESOURCES

Free World reserves of molybdenum are estimated at 2,500 million pounds of molybdenum. Of this, about 85 percent occurs in 4 deposits, 3 in the United States and 1 in Chile (table 1).

TABLE 1.—*Four deposits that contain 85 percent of the world's molybdenum resources*

Deposit	Country	Major ownership
Climax	United States	Climax Molybdenum Co.
Utah Copper	do	Kennecott Copper Corp.
San Manuel	do	San Manuel Copper Corp. (subsidiary of Magma Copper Co.).
Chuquicamata	Chile	The Anaconda Co.

The United States alone contains about 90 percent of the world's molybdenum reserves and provides about 90 percent of the world's production (fig. 1). The commercial reserves of the United States and Alaska are estimated at 2,200 million pounds of molybdenum. Except for byproduct sources, these reserves are in ores that contain over 0.50 percent MoS_2. Additional potential resources in the United States and Alaska are estimated at about 850 million pounds of molybdenum. Except for byproduct sources, the latter occur in deposits that contain 0.25 to 0.50 percent MoS_2. About 94 percent of these reserves occur in 5 deposits (table 2).

TABLE 2.—*Five deposits that contain 94 percent of United States molybdenum resources*

Deposit	Location	Major ownership
Climax	Colorado	Climax Molybdenum Co.
Utah Copper	Utah	Kennecott Copper Corp.
San Manuel	Arizona	San Manuel Copper Corp. (subsidiary of Magma Copper Co.).
Morenci	do	Phelps Dodge Corp.
Orange Hill	Alaska	

No other deposit contains more than 0.1 percent of the domestic resources, and the following porphyry-copper deposits in total contain only about 0.3 percent of the domestic molybdenum reserves: Chino, New Mexico; Nevada Mines, Nevada; Miami, Arizona; Bagdad, Arizona; and Silver Bell, Arizona.

Since 1940 about 40 percent of the domestic production of molybdenum has come from byproduct sources and about 60 percent from Climax. For individual years, however, the ratio has varied considerably, as Climax has produced as much as 75 percent and as little as 43 percent of the total. Climax was the most productive during World War II and after 1951. The byproduct sources, listed in order of current molybdenum production, follow: Utah Copper, Morenci, Chino, Miami, Nevada Mines, Pine Creek, and Bagdad. Because byproduct sources are not as dependent on market prices and demand for molybdenum as Climax, byproduct yield should be steadier as long as the demand and price for copper remain strong.

The bulk of potential domestic resources is associated with the higher grade ores in the Climax deposit. Additional potential resources are in porphyry-copper deposits that, because of grade of copper or location, are not currently commercial, such as the Glacier Peak deposit, Washington; the Loma Prieta and Copper Hill deposits in Copper Basin, Arizona; and the Orange Hill deposit, Alaska. Additional marginal reserves also occur in numerous small vein or fracture stockwork deposits in which molybdenite is the principal ore mineral, such as the Big Ben deposit, Montana; the Hall deposit, Nevada; the Boy Scout and Moss-Dryden deposits, North Carolina; and the Starr deposit, Washington. Most of these deposits have reserves of only a few million pounds each, but additional exploration probably would increase them.

The quality of information on foreign molybdenum resources is variable. Some good information is available for Canada, Mexico, South America, and part of Europe, but reliable information is not available for European Russia and Asia. These latter areas may have significant molybdenum resources.

Production of molybdenum has been reported from Chile, Peru, Finland, Norway, French Morocco, Greece, Manchuria, Australia, Korea, Japan, Russia, and other countries. Based on production data, only the deposits in Chile, Mexico, Canada, and Norway are important, and even these deposits have little importance compared with domestic production.

The molybdenum resources of Chile, Mexico, Canada, and Norway can be evaluated on the basis of the geologic occurrences of the deposits. Commercial reserves of the known deposits in these 4 countries are estimated at 300 million

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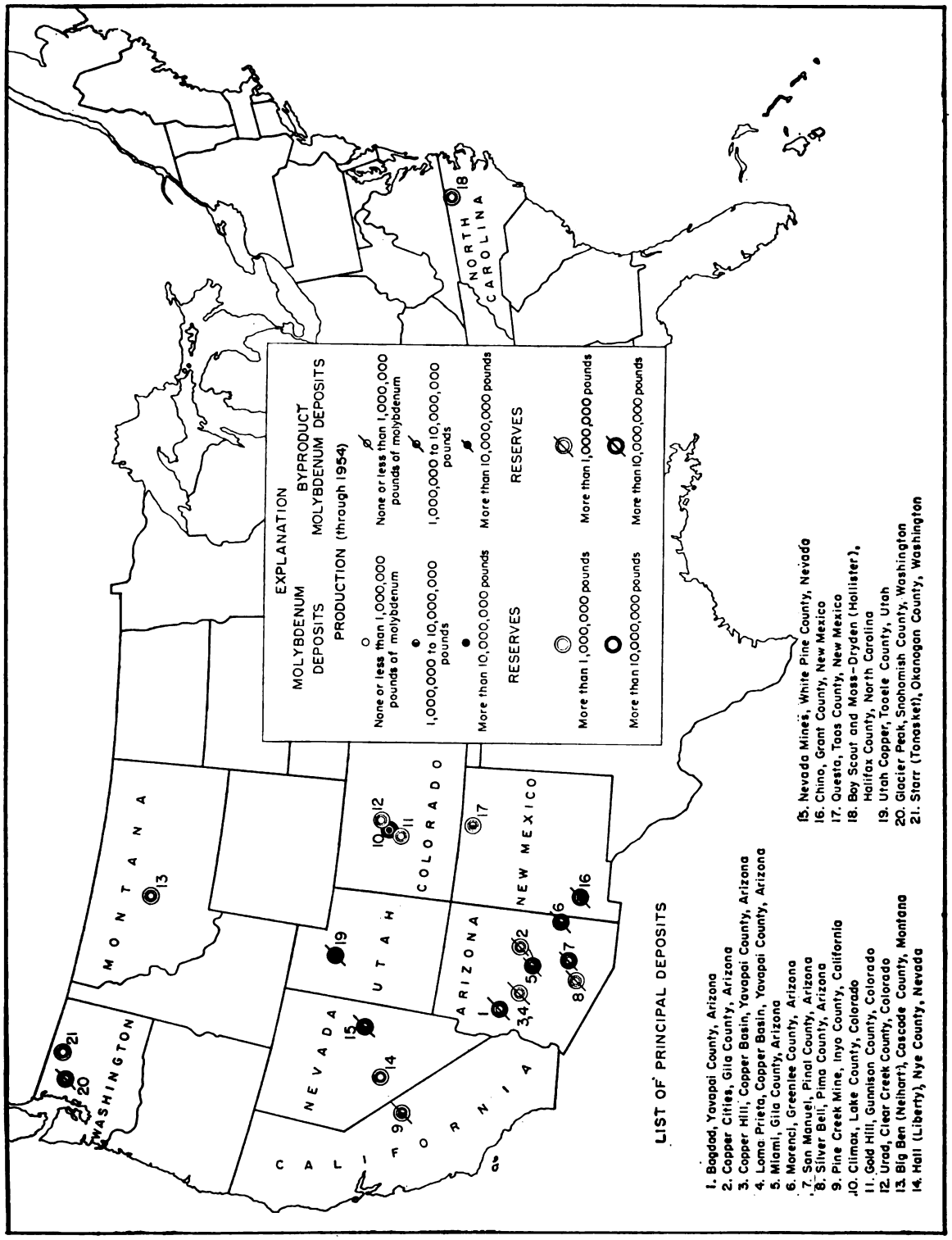
EXPLANATION
MOLYBDENUM DEPOSITS
BYPRODUCT MOLYBDENUM DEPOSITS
PRODUCTION (through 1954)
None or less than 1,000,000 pounds of molybdenum
1,000,000 to 10,000,000 pounds
More than 10,000,000 pounds
None or less than 1,000,000 pounds of molybdenum
1,000,000 to 10,000,000 pounds
More than 10,000,000 pounds
RESERVES
RESERVES
More than 1,000,000 pounds
More than 10,000,000 pounds
More than 1,000,000 pounds
More than 10,000,000 pounds
MONTANA
WASHINGTON
NEVADA
CALIFORNIA
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH CAROLINA
LIST OF PRINCIPAL DEPOSITS
1. Bagdad, Yavapai County, Arizona
2. Copper Cities, Gila County, Arizona
3. Copper Hill, Copper Basin, Yavapai County, Arizona
4. Lomo Prieta, Copper Basin, Yavapai County, Arizona
5. Miami, Gila County, Arizona
6. Morenci, Greenlee County, Arizona
7. San Manuel, Pinal County, Arizona
8. Silver Bell, Pima County, Arizona
9. Pine Creek Mine, Inyo County, California
10. Climax, Lake County, Colorado
11. Gold Hill, Gunnison County, Colorado
12. Urad, Clear Creek County, Colorado
13. Big Ben (Neihart), Cascade County, Montana
14. Hall (Liberty), Nye County, Nevada
15. Nevada Mines, White Pine County, Nevada
16. Chino, Grant County, New Mexico
17. Questa, Taos County, New Mexico
18. Bay Scout and Moss-Dryden (Hollister), Halifax County, North Carolina
19. Utah Copper, Tooele County, Utah
20. Glacier Peak, Snohomish County, Washington
21. Starr (Tonasket), Okanogan County, Washington

FIGURE 1.—Distribution of Principal Production and Reserves of Molybdenum in the United States.

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pounds of molybdenum, of which the great bulk is in the Chilean porphyry-copper deposits. Additional deposits probably will be discovered, and it is believed that the major discoveries will be porphyry-copper deposits that will yield molybdenite as a byproduct.

MINERALOGY AND GEOLOGY

MINERALOGY

Molybdenite and, to a minor extent, wulfenite are the commercially important minerals of molybdenum. Powellite and ferrimolybdite (molybdite), which are oxidation products of other minerals, are widespread in small quantities, but they have not been treated commercially. The physical and chemical properties of the principal molybdenum minerals are summarized in table 3.

Molybdenite (MoS_2) is a lead-gray, metallic mineral that characteristically occurs in thin, tabular, commonly hexagonal plates and, to a smaller extent, in rosettes. It has perfect basal cleavage and is soft and flexible but not elastic. Superficially it resembles graphite, for which it commonly has been mistaken.

Wulfenite ($PbMoO_4$) is a heavy mineral with a resinous or adamantine luster. It ranges in color from a dirty white through pale yellow, yellow, and yellow orange to orange or orange red. It generally occurs in well-formed crystals, chiefly square tabular, which are sometimes extremely thin.

Powellite is a powdery mineral of variable color, including dirty white, gray, straw yellow, greenish yellow, pale greenish blue, blue, and brown. Its composition ($CaMoWO_4$) is variable; tungsten substitutes for molybdenum up to about Mo:W=9:1. Apparently, however, a complete series to scheelite ($CaWO_4$) does not exist in natural material. Powellite fluoresces creamy yellow to golden yellow in ultraviolet light; this fluorescence is characteristic.

Ferrimolybdite (molybdite) is a very soft, hydrous mineral of distinctive canary-yellow color. Its composition is probably $Fe_2(MoO_4)_3 \cdot 8H_2O$, but the water content is uncertain and decreases with temperature. Dehydration is complete at 250° C. Ferrimolybdite occurs as earthy powder, fibrous crusts, and tufted or radial fibrous aggregates.

GEOLOGY

Molybdenum occurs principally in four types of deposits: (1) Those that yield molybdenum alone or as the chief metal, (2) copper deposits that yield molybdenum as a byproduct, (3) contact-metamorphic tungsten deposits that yield molybdenum as a byproduct, and (4) wulfenite-bearing base-metal deposits. The first 2 types contain 99 percent of the known molybdenum resources. The last two types have been the most productive of numerous miscellaneous byproduct sources. Molybdenum also occurs in vanadiferous shales, which, although very low grade, contain total quantities far exceeding those of the other sources of miscellaneous byproducts. The molybdenum of these shales has not been included in the estimates of reserves, however, because it is questionable whether future techniques of recovery and mine development will make it economical.

The deposits that contain molybdenite as the sole or principal ore mineral range from quartz veins related to aplites and pegmatites through quartz veins and stockworks whose parentage

TABLE 3.—*Physical and chemical properties of principal molybdenum minerals*

Properties	Molybdenite	Wulfenite	Powellite	Ferrimolybdite
Composition	MoS_2	$PbMoO_4$	$Ca(Mo,W)O_4$	$Fe_2(MoO_4)_3.8H_2O$.
Mo——percent	60.0	26.1	39–48 (approx.)	39 (approx.)
Crystal system	Hexagonal	Tetragonal	Tetragonal	Orthorhombic (?).
Cleavage	Perfect in 1 direction	Perfect in 4 directions	Indistinct	
Specific gravity	4.62–4.73	6.5–7.0	4.23–4.53	3.0 (approx.).
Color	Lead-gray	Ranges from grayish white through yellow to orange and orange red.	Ranges from straw yellow to dirty white.	Sulfur yellow.
Tenacity	Flexible	Brittle		Powdery.
Luster	Metallic	Adamantine or resinous.	Subadamantine or pearly or greasy.	Silky to earthy.
Fracture	None	Uneven	Uneven	None.
Hardness [1]	1–1½	3	3½–4	1½.
Streak	Bluish gray on paper, greenish on porcelain or glazed paper.	White	White	Pale yellow.

[1] Mohs' scale.

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is uncertain, to quartz veins, stockworks, and general silicification definitely related to specific porphyry stocklike intrusions.

Small quantities of molybdenite occur in quartz veins associated with aplites and pegmatites, as well as in the aplites and pegmatites themselves.

The molybdenite commonly occurs in large rosettes, which are valued highly as mineral specimens. The molybdenite-bearing parts of these veins, however, are podlike and without leads to other pods, so that production usually stops with mining of a single pod. Deposits of this type have not yielded significant amounts of molybdenum in the past, and it is unlikely that they will do so in the foreseeable future.

The simple quartz vein and stockwork deposits are most abundant, but only a few (Climax and Urad, Colorado; Questa, New Mexico; and La Corne, Quebec) have yielded significant quantities of molybdenite. The production from these has been large enough to encourage the search for others.

The mineralogy of these vein and stockwork deposits is variable. Some veins that contain only quartz and molybdenite have not been productive. Others that have been productive contain, in addition to quartz and molybdenite, small amounts of base-metal sulfides, pyrite fluorite, carbonates, and secondary silicates. Presumably they are related to acid hypabyssal or plutonic rocks, which may or may not be exposed at the surface. The Climax deposit illustrates the transition both horizontally and in depth from a stockwork of quartz veins in country rock to a stockwork in and related to a quartz-monzonite intrusion.

All the copper deposits with byproduct molybdenum are somewhat similar in origin and occurrence. Each consists of an acid hypabyssal intrusion and a locally mineralized and fractured zone that includes part or all of the intrusive and commonly some of the contiguous country rock. In most porphyry-copper deposits the fractured and brecciated zone resulted from deformation after solidification of the intrusive. The fractures, which commonly occur in sets, provided the "plumbing system" that guided and distributed the mineralizing fluids.

The chief primary minerals of porphyry-copper deposits are quartz, pyrite, chalcopyrite, and molybdenite. In addition, minor amounts of other base-metal minerals, specular hematite, fluorite, and secondary silicate minerals are commonly present. Chalcocite replaces pyrite and chalcopyrite in the zone of secondary enrichment. Many copper oxide minerals, chiefly chrysocolla, azurite, malachite, and chalcanthite, occur in the zone of oxidation. Leaching—the process used to recover copper from oxidized ores—does not permit economic recovery of the small quantities of molybdenum.

The average ratio of copper to molybdenum in the prophyry-copper ores is estimated to be about 100:1. It ranges, however, from about 50:1 to perhaps 150:1.

Small quantities of molybdenum are widely distributed in lime-silicate deposits along the contacts between granitic intrusive rocks and lime-rich sedimentary rocks. The only domestic production from this type has been as a byproduct from the Pine Creek tungsten mine in California. The mineral assemblage of this type of contact deposit is quite simple and constant. Varying quantities of chalcopyrite, bornite, scheelite, pyrite, and molybdenite occur in a lime-silicate contact zone of garnet, diopside, quartz, and a few other contact-metamorphic minerals.

In many places the size, shape, and distribution of the ore bodies indicate that mineralization was controlled by preore fracturing of the lime-silicate rock. In some contact deposits more than one generation of fractures and concomitant mineralization can be recognized. In the Pine Creek mine, for example, molybdenite is younger than scheelite, and distribution of the former is not coextensive with that of the latter. Molybdenite output from contact deposits has been small, and it is unlikely that such deposits will become major producers.

The oxidized parts of some lead-zinc deposits in arid and semiarid regions of the world contain wulfenite, commonly associated with vanadium minerals, such as vanadinite and descloizite. The origin of these molybdenum and vanadium minerals is obscure. In most deposits the molybdenum and vanadium apparently were introduced after oxidation of the deposit because analyses of the primary vein minerals fail to reveal enough molybdenum and vanadium to account for that present in the oxidized portions of the vein. Adjacent vanadium- and molybdenum-bearing shales are commonly accepted as the source; but in some deposits, such as that in the Mammoth mine, Arizona, such shales are not present. Production from this type of deposits has been small and is not likely to be significant in the future.

UNITED STATES DEPOSITS

ALASKA

ORANGE HILL

Orange Hill is on the east side of the Nebesna River about 12 miles south of the terminus of the Nebesna Road, a branch of the Richardson Highway. Molybdenum, copper, gold, and silver minerals occur in quartz diorite adjacent to limestone, graywacke, and greenstone of Permian age. Molybdenite is present in many

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quartz veins and also is disseminated as flakes in the quartz diorite. The deposits have been explored by 8 tunnels with an aggregate length of 225 feet and 19 diamond-drill holes totaling 3,187 feet.

SHAKAN, KOSCIUSKO ISLAND

Molybdenite occurs in a vein 5.8 feet wide and 120 feet long in hornblende diorite that has been explored by 14 opencuts and 570 feet of tunnels. The associated sulfide minerals are pyrrhotite, pyrite, chalcopyrite, and sphalerite. Some quartz and silicate minerals are present.

ARIZONA

BAGDAD COPPER CORP., YAVAPAI COUNTY

Bagdad is a porphyry-copper deposit. Molybdenite occurs in veins associated with pyrite, orthoclase, and quartz and in veinlets associated with quartz alone. It appears to be younger than chalcopyrite and is only associated with chalcopyrite at or near vein intersections. Production has been reported intermittently since 1944.

COPPER CITIES MINING CO., GILA COUNTY

The Copper Cities deposit, north of Miami in central Arizona, is held by a subsidiary of Miami Copper Co. The deposit is not yet in production, but it is believed that plans do not include a recovery unit for molybdenite.

The Copper Cities deposit occurs in quartz monzonite and granite porphyry. It consists of primary quartz, pyrite, chalcopyrite, and molybdenite in veinlets and disseminated in the granite rock between the veinlets. Pyrite is the most abundant sulfide, followed by chalcopyrite. Molybdenite occurs with quartz in veinlets.

The molybdenite content of the ore has been estimated at 0.004 percent, which is much lower than that of the other disseminated deposits in the district (Miami-Inspiration and Castle Dome).

COPPER HILL MINE, COPPER BASIN, YAVAPAI COUNTY

The Copper Hill mine is a porphyry-copper deposit in Copper Basin, 11 miles west of Prescott, Ariz. Over 1,200 feet of underground workings and 11 diamond-drill holes totaling 1,475 feet explored the mineralized zone. There has been a small production of copper carbonate and molybdenite ore.

The mineralized zone is in quartz diorite, which has been brecciated, altered, silicified, and mineralized with chalcopyrite and molybdenite to form a breccia pipe almost 400 feet in diameter.

LEVIATHAN MINE, MOJAVE COUNTY

The Leviathan mine is in the Hualapai Mountains south of Kingman, Ariz., and 32 miles east of Yucca. It is developed by a steeply inclined shaft 265 feet deep, which is connected to 2 levels along the vein.

Molybdenite and chalcopyrite occur in a quartz vein that strikes N. 35° E. and dips 80° NW. The country rock is quartz diorite. The vein ranges in width from 2 to 20 feet and averages 3½ feet. A parallel vein carrying molybdenite crops out 450 feet northwest of the shaft, and 2 similar quartz veins crop out half a mile southeast.

LOMA PRIETA MINE, COPPER BASIN, YAVAPAI COUNTY

The Loma Prieta mine is a porphyry-copper deposit in Copper Basin about 11 miles west of Prescott, Ariz. The mine is opened by a vertical shaft 414 feet deep, connected with 1,170 feet of drifts on 4 levels. Two or three cars of copper sulfide ore have been produced.

The ore consists of brecciated quartz diorite cemented by quartz veins carrying pyrite, chalcopyrite, and molybdenite. The deposit, as defined by a cutoff grade of 0.45 percent copper, is a vertical pipe of mineralized breccia having a cross-sectional area at the 400 level of 60,000 square feet.

MIAMI COPPER CO., GILA COUNTY

The Miami deposit, at the town of Miami in central Arizona, is a porphyry-copper deposit from which molybdenum has been recovered as a byproduct since 1938.

The occurrence of molybdenum in the Miami deposit is similar to that in other porphyry-copper deposits; molybdenite occurs in quartz veins associated with pyrite and chalcopyrite and is disseminated to a small extent in the country rock between the veins.

MORENCI BRANCH, PHELPS DODGE CORP., GREENLEE COUNTY

Morenci is a disseminated-copper deposit in eastern Arizona not far from the New Mexico border. Molybdenite has been recovered continuously since 1951.

The Morenci deposit is entirely within quartz-monzonite porphyry that has been intensely argillized and sericitized. Numerous large to small cracks along veins break the rock into small, angular fragments. The veins and veinlets consist of quartz, pyrite, chalcopyrite, chalcocite (replacing pyrite and chalcopyrite), and small but variable amounts of molybdenite. The distribution of molybdenite in the ore is erratic, and the average molybdenite content is not known.

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NEW YEARS EVE AND ESPERENZA MOLYBDENUM PROSPECTS, PIMA COUNTY

The New Years and Esperenza molybdenum prospects are in the Pima mining district on the eastern flank of the Sierrita Mountains about 30 miles south of Tucson, Ariz. The S. W. Shattuck Chemical Co. produced 31 tons of concentrate from the New Years Eve deposit in 1951.

Near the New Years Eve, the most favorable ground for molybdenum production is an elongated quartz "blowout" in granodiorite near a quartzite contact. The quartz is mineralized below the adit level for an exposed vertical distance of 75 feet. Chalcopyrite and molybdenite occur in erratic seams and bunches in the quartz.

The Esperenza claims are in Coporos Gulch, 1 mile southwest of the New Years Eve mine. Here a silicified breccia was formed from quartzite and kaolinized and sericitized grandiorite porphyry and diorite. Sparse chalcopyrite and molybdenite occur in the silicified breccia and in quartz veins in the kaolinized rocks.

SAN MANUEL COPPER CORP., PINAL COUNTY

The San Manuel deposit is in southern Arizona about 40 miles north of Tucson. It was discovered during World War II and has been under continuous exploration and development since its discovery. Plans called for the recovery of molybdenite, and production commenced early in 1956 at an average rate of about 35,000 tons of ore per day.

San Manuel is a typical porphyry-copper deposit. The primary ore consists chiefly of pyrite, chalcopyrite, a small quantity of bornite, and even less molybdenite in monzonite porphyry and contiguous rocks. There is some secondary enrichment; pyrite and chalcopyrite have been partly replaced by chalcocite. The molybdenite occurs with quartz in veinlets, some of which are younger and some older than quartz-chalcopyrite veinlets.

SILVER BELL PROPERTY, AMERICAN SMELTING & REFINING CO., PIMA COUNTY

Silver Bell is a small porphyry-copper property in south-central Arizona. Production began in 1954 at the rate of 18,000 tons of copper annually; daily ore production is about 7,500 tons.

The disseminated ore is in 2 deposits, the Oxide and the El Tiro, separated by about 2 miles. The deposits occur chiefly in alaskite, dacite porphyry, and monzonite. They appear to be genetically related to the monzonite, which is a stock and is the youngest of the intrusives. Primary mineralization introduced quartz, pyrite, and chalcopyrite, chiefly in narrow, parallel veins and veinlets. To a small extent, pyrite and chalcopyrite are disseminated between the veins. The veins range in width from paper thin to several inches and in spacing from inches to several feet. The limits of the ore are controlled by the spacing of the veins. Not much information is available on the occurrence of the molybdenite. Presumably its occurrence is similar to that of the chalcopyrite, chiefly in veins and veinlets, and to a smaller extent disseminated in the ore between veins.

CALIFORNIA

PINE CREEK MINE, U. S. VANADIUM CORP., INYO COUNTY

The Pine Creek mine is near the crest of the Sierra Nevada west of Bishop, Calif. The mine is opened to a depth of 2,250 feet. It produced intermittently from 1917 to 1936 and continuously since 1939. Output in 1955 was at the rate of about 500 tons per day.

The mine is near the north end on the west side of the Pine Creek pendant in a contact zone between marble and intrusive granite and quartz diorite. The contact zone consists mainly of garnet-diopside tactite but includes quartz and quartz-feldspar rocks. Thicker portions of the contact zone constitute the tungsten ore bodies. The upper third of the ore zone contained about 0.6 percent molybdenum, about 0.2 percent copper, and 0.45 percent WO_3. The molybdenum content decreased with depth and is much less important in the lower workings. The lower tunnel level, which is about 1,500 feet lower than the lowest working level of the mine, encountered tungsten ore carrying a small amount of molybdenite.

COLORADO

CLIMAX MOLYBDENUM CO., LAKE COUNTY

The Climax deposit is 1 mile east of Fremont Pass in Lake County about 100 miles west of Denver and 13 miles north of Leadville. The ore is mined by block caving and taken directly to the mill through two main haulage tunnels.

In the vicinity of the Climax deposit Tertiary dikes and stocks cut Paleozoic sedimentary rocks, Precambrian crystalline schists of the Idaho Springs formation, and the Precambrian Silver Plume granite. The Tertiary stock (Climax porphyry stock), which is associated with the Climax deposit, is quartz monzonite. In the area of the deposit the Climax porphyry stock does not crop out, but it has been well exposed by underground openings. The rock overlying the stock, chiefly Silver Plume granite, was intensely silicified to form a domical cap of quartz rock to which the ore is peripheral.

The wall rocks and the Climax stock in the ore zone were closely fractured, presumably during Laramide or later time. Mineralization of

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these channels formed a close stockwork of veinlets that average an eighth to half an inch in width. The rock between the veinlets in the ore zone was also intensely mineralized, presumably by diffusion through minute fractures and pore spaces. Three types of veins have been recognized. They are listed below, with the minerals found in them:

Molybdenite-quartz veins:	
Quartz	Sericite
Molybdenite	Orthoclase
Pyrite	Fluorite
Pyrite-topaz-quartz veins:	
Quartz	Galena
Pyrite	Sphalerite
Topaz	Rhodochrosite
Hübnerite	Sericite
Chalcopyrite	Fluorite
Sericite and topaz veins:	
Sericite	Kaolinite
Topaz	Montmorillonite

These minerals also occur in the altered wall rocks.

The shape of the ore zone is irregular in three dimensions. In plan on the upper levels it was shaped like a doughnut, with the quartz rock in the center; but on the lower levels, where the volume of quartz rock is less and more Climax porphyry is exposed, the ore zone loses its regularity. On all levels the area of ore is most impressive.

GOLD HILL MINE, GUNNISON COUNTY

The Gold Hill mine is on the western flank of the Sawatch Range, 10 miles north of Pitkin and 5 miles south of Tincup, Gunnison County, Colo.

Gold Hill consists of Precambrian gneissic quartz monzonite, flanked on the northeast and southwest by lower Paleozoic sedimentary rocks that are cut by porphyritic intrusives of Laramide age. The ore occurs in veins, nearly all of which are in the Precambrian quartz monzonite, although a few extend into the Cambrian quartzites. The veins are relatively short fissures filled by quartz that contains some pyrite and small amounts of hübnerite, molybdenite, and chalcopyrite. The strongest molybdenum-bearing veins strike nearly east, and the tungsten-bearing veins strike northeast. Molybdenite is also present in a group of north-northwest veins that appear to be related to two strong faults with the same trend.

URAD MINE, CLEAR CREEK COUNTY

The Urad mine of the Molybdenum Corporation of America is on the southern slope of Red Mountain, about 1½ miles from U. S. Highway 40, a few miles southwest of Berthoud Pass. The lower tunnel and mill are at an altitude of 10,110 feet. These are connected by a 1,100-foot raise to upper workings at 11,200 to 11,400 feet altitude.

Molybdenite occurs in vein systems in altered granite close to the walls of a small stock of rhyolite porphyry. These vein systems rim the southern contact of the rhyolite stock and dip 45° to 60° northward, penetrating the porphyry body. An altered zone well exposed at the surface encircles the rhyolite stock, but molybdenite has been found only on the south side. The vein systems on the south side form essentially a stockwork of subparallel veins and subsidiary fractures in the workings above 11,000 feet. The main east-west veins, which are more or less parallel, are several feet wide and contain rich concentrations of molybdenite in subsidiary fractures in the hanging and foot walls.

MONTANA

BIG BEN (NEIHART) MOLYBDENUM DEPOSIT, CASCADE COUNTY

The Big Ben molybdenum deposit is in the Neihart mining district, Cascade County, Mont., about 2½ miles airline northeast of the town of Neihart.

The development work consists of 2 adits, 275 and 310 feet long, and about 500 feet of surface trenches. Four diamond-drill holes aggregating 1,385 feet were sunk in 1944. Ore has not been shipped from the property.

The rocks in the area include Precambrian gneisses and schists, a partly gneissoid diorite, and two types of younger porphyries of unknown age. The molybdenite and associated gangue minerals, chiefly pyrite and quartz, occur in a stockwork and as disseminations in the rock, which is locally silicified and, to a smaller extent, kaolinized in the mineralized zone. In general, the silicified zones contain the most molybdenite. The shape of the mineralized zone that contains the most molybdenite is thought to be elliptical in plan and to have nearly vertical sides.

NEVADA

HALL (LIBERTY) MOLYBDENUM PROPERTY, NYE COUNTY

The Hall deposit is in the San Antonio Mountains (sometimes called the Liberty Mountains), Nye County, Nev., about 20 miles north of Tonopah. Development work consists of an inclined shaft 310 feet deep and 3 connecting levels of drifts and crosscuts.

Limestone, which locally is silicified, unconformably overlies mica schist and sericitic quartzite in the vicinity of the Hall deposit. All three units are intruded by a small alaskite stock. Quartz veins occur in the border of the alaskite stock and in the mica schist near the contact with the stock, but molybdenite occurs only in the veins in the mica schist, and to a smaller extent in those along the contact between the schist and the stock.

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Andesite dikes, in part paralleling the mineralized zone, are definitely later than the mineralization.

NEVADA MINES DIVISION, KENNECOTT COPPER CORP., WHITE PINE COUNTY

Nevada Mines is in eastern Nevada near Ely. The company concentrator at McGill also treats the ores from Consolidated Coppermines' Emma-Nevada deposit, which joins the Copper Flat ore body of Nevada Mines on the west and is really the westward extension of it. Nevada Mines has been a consistent producer of copper since 1908, but molybdenum recovery dates only from 1941.

Nevada Mines is a porphyry-copper deposit that consists of quartz-monzonite stocks mineralized with quartz-pyrite-chalcopyrite veinlets and disseminated pyrite and chalcopyrite. Molybdenite only occurs in minor amounts in the quartz veinlets and as "smears" along fracture surfaces.

NEW MEXICO

CHINO MINES DIVISION, KENNECOTT COPPER CORP., GRANT COUNTY

The Chino porphyry-copper deposit is at Santa Rita in southwestern New Mexico. It produces about 23,000 tons per day of ore that averages a little better than 1 percent copper and a small amount of molybdenum.

The ore consists of shattered and brecciated quartz-diorite and granodiorite, mineralized with quartz, sericite, and sulfide minerals. The sulfides, which are in veins and disseminated between veins, consist of pyrite, chalcocite, chalcopyrite, and small amounts of molybdenite and bornite.

QUESTA MINE, MOLYBDENUM CORPORATION OF AMERICA, TAOS COUNTY

The Questa deposit is in a tributary of the Red River about 7 miles east of the town of Questa. Production in 1944 was 50 tons per day of ore that was hand-sorted to 3 to 4 percent MoS_2. Mine ore varies from 2 to 15 percent MoS_2; concentrate contains about 80 percent MoS_2.

The Questa deposit is a typical fissure-vein deposit and the only one of its kind known to have produced appreciable amounts of molybdenite. In the vicinity of the deposit an albite granite intrudes Precambrian schist and a series of sedimentary and volcanic rocks of uncertain age. The veins are in the granite in a zone not over 100 feet across immediately below the contact with the schist, but small seams of molybdenite occur over a much greater width. The veins branch and die out in the overlying altered schist and shaly sedimentary rock.

NORTH CAROLINA

BOY SCOUT AND MOSS-DRYDEN (HOLLISTER) MOLYBDENUM PROSPECTS, HALIFAX COUNTY

The Boy Scout and Moss-Dryden molybdenum prospects are in Halifax County, northeastern North Carolina, 15 miles west of Enfield and 21 miles southeast of Warrenton.

The deposits occur as veins in a small granitic body near the eastern edge of the Piedmont province. Vein material consists of quartz, molybdenite, pyrite, and small amounts of chalcopyrite and fluorite. The 2 known mineralized zones (Boy Scout and Moss-Dryden) are about 2 miles apart at either end of the granitic mass. The veins are in granite but near the contact with overlying foliated rocks.

In the Boy Scout prospect are several well-defined veins, of which the Jones vein (about 1,000 feet long) is the strongest. Much of the molybdenite is contained, however, in numerous short veins that appear to form a network of connecting veins along the plunging nose of the granitic body. In the Moss-Dryden prospect the Dryden vein is the strongest. It has a strike length of about 1,800 feet.

UTAH

UTAH COPPER DIVISION, KENNECOTT COPPER CORP., SALT LAKE COUNTY

Utah Copper is at Bingham in east-central Utah. It is the largest porphyry-copper deposit in the United States and the second largest producer of molybdenum. Utah Copper mills about 90,000 tons of ore a day that contains about 1 percent copper and a small quantity of molybdenum.

The host rock at Bingham is a monzonite porphyry. The ore consists of quartz and sulfides in veinlets cutting the porphyry and disseminated between the veinlets. The most abundant primary and secondary minerals are chalcopyrite, chalcocite, covellite, bornite, pyrite, magnetite, and quartz. Molybdenum occurs in small amounts, chiefly in quartz veins.

WASHINGTON

GLACIER PEAK, SNOHOMISH COUNTY

Glacier Peak is in sec. 10, T. 31 N., R. 15 E., Snohomish County, Wash. It is reached from Darrington by 30 miles of dirt road and 12 miles of pack trail. The deposit has been explored by 6 tunnels that total 900 feet in length and by 36 diamond drillholes totaling 20,500 feet. There has been no mining.

Glacier Peak is a small porphyry-copper deposit containing copper and molybdenum minerals disseminated through granitic rocks and

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in quartz veinlets. The sulfide minerals are chalcopyrite, pyrite, molybdenite, and pyrrhotite.

STARR (TONASKET) MOLYBDENUM MINE, OKANOGAN COUNTY

The Starr molybdenum mine, Okanogan County, Wash., is about 5 air-line miles west of Tonasket in the north-central part of the State. The mineralized zone has been explored to a depth of 250 feet by means of 3 adit levels, 1 sublevel, and a raise that connects 2 of the adits and the sublevel. In all, there is about 2,700 feet of underground workings.

The country rock is a biotite-hornblende granodiorite. The mineralized zone is brecciated and stands nearly vertical in the granodiorite. The brecciation may have resulted from jointing and local intense fracturing along intersecting faults.

The granodiorite in the breccia zone is more or less intensely silicified. Quartz veins and irregular stringers and blebs of vein quartz are common throughout the zone. Molybdenite and pyrite occur in veinlets and as disseminated flakes and grains in the silicified granodiorite.

FOREIGN DEPOSITS

ASIA

The size and rate of growth of the molybdenum industry in Asia (including all of the Soviet Union) are unknown. The Bureau of Mines Minerals Yearbook for 1947 states that Soviet production was reported to have increased fourfold between 1940 and 1945 and that additional plans called for doubling the 1945 production by 1950. The Kounrad porphyry-copper deposit near Lake Balkhash is suspected to account for the bulk of the proposed increase in production and for the bulk of the known molybdenum resources. The Tyrny-Auz tungsten-molybdenum deposit in the North Caucasus is the second largest known source, but the potential of this type of deposit is small compared with that of porphyry-copper deposits. Development was also underway on at least five other molybdenum deposits in the Soviet Union, according to the 1947 Minerals Yearbook. Until further information on deposits in Asia is available, any attempt to estimate its molybdenum resources is idle speculation. It should be emphasized, however, that we have no basis for assuming that the ultimate production potential is low. The existence of porphyry-copper deposits suggests that Asia may have considerable molybdenum resources.

CANADA

Molybdenum production in Canada has been from vein-type deposits. During World War II, production reached a peak of about 1,120,000 pounds a year under the stimulation of Government support. Subsequently production declined, and only the La Corne deposit, Abitibi County, Quebec, has remained in production.

The known molybdenum resources of Canada are small and will remain so as long as the only molybdenum reserves are in vein deposits.

MEXICO

Before 1947 Mexico produced substantial quantities of molybdenum, which, from 1940–47, amounted to about 3 percent of the world supply. This came chiefly, if not wholly, from the Cananea deposit, and cessation of molybdenum production from this deposit coincided roughly with depletion of the famous Colorado ore body, which contained substantial quantities of molybdenite. No other major sources of this metal are known in Mexico.

NORWAY

Molybdenum production from Norway comes largely from the Knaben mine, which includes several different localities. Through 1950, this mine had produced about 9,900 tons of molybdenite concentrate, as compared with 1,100 tons for all other deposits in Norway. Concentrating capacity of the Knaben plant is about 800 tons per year.

At Knaben molybdenite occurs in poorly defined veins and as disseminated flakes oriented parallel to foliation of gneissic rocks. Associated introduced minerals include minor quantities of pyrite, other sulfides, silicates, tungstates, calcite, fluorite, apatite, and magnetite.

Reports of the grade of the Knaben ore differ; early reports set the grade at 0.25 to 0.50 percent molybdenite, whereas more recent ones indicate 0.15 to 0.20 percent. Probably the ore mined during the early years of the deposit was of higher grade. This type of deposit characteristically does not contain large measurable reserves; however, possible ore reserves are large, though of low grade.

SOUTH AMERICA

Chile is the major producer of molybdenum outside the United States. The Braden porphyry-copper deposit supplies almost the entire production, but the future promise for additional molybdenum from other porphyry-copper deposits, such as Chuquicamata, is great.

Mining in the Chuquicamata deposit is progressing from the oxidized ores, where recovery of small amounts of molybdenum is not feasible, to sulfide ores, where it is. Molybdenite is known to occur in the sulfide ores, and the large reserves at Chuquicamata constitute a major resource of molybdenum.

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It is not known whether the recently discovered porphyry-copper deposits at Toquepala, Quellaveco, and Caujone, all in Peru and all to be exploited by the Southern Peru Copper Corp., do or do not contain molybdenite, but the presumption is that they do. Because production will be largely from sulfide ores where recovery of molybdenite is feasible and because the combined ore reserves of the 3 deposits have been estimated at 1,000 million tons, these deposits constitute a major potential resource of molybdenum.

Additional porphyry-copper deposits probably will be discovered in South America, and it is also probable that some if not most of these will produce byproduct molybdenite.

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SUPPLY—DEMAND

Only in war periods has the supply of molybdenum been less than demand, and then the shortage was due to its being substituted for alloying elements that were in more critical supply and to inability to increase mine and mill capacity quickly to keep pace with higher demand.

SUPPLY

Molybdenum supply is derived both from ore mined chiefly for molybdenum and as a byproduct from copper and tungsten ores. Of the estimated total supply of molybdenum through 1955, the United States produced 87 percent, Chile 3 percent, Mexico 2 percent, and Norway 1 percent; the remaining 7 percent was mostly produced in Canada, Yugoslavia, Australia, Japan, and Peru. Approximately 65 percent of the supply comes from mines operated chiefly for molybdenum, and 35 percent is recovered as a byproduct from copper and tungsten ores.

UNITED STATES

In 1955 seven firms operating mines in Colorado, Utah, Arizona, New Mexico, California, and Nevada comprised the molybdenum-mining industry of the United States and produced 92 percent of the total estimated world output. During the first half of 1956 two new firms (San Manuel Copper Corp. and American Smelting & Refining Co.) began byproduct recovery of molybdenum from their copper mines in Arizona. United States firms producing molybdenum in 1956 were:

Climax Molybdenum Co., 500 Fifth Ave., New York, N. Y.
Kennecott Copper Corp., 161 East 42d St., New York, N. Y.
Phelps Dodge Corp., 40 Wall St., New York, N. Y.
Union Carbide Nuclear Co., a division of Union Carbide & Carbon Corp., 30 East 42d St., New York, N. Y.
Miami Copper Co., 61 Broadway, New York, N. Y.
Bagdad Copper Corp., Bagdad, Ariz.
Molybdenum Corp. of America, 500 Fifth Ave., New York, N. Y.
San Manuel Copper Corp., San Manuel, Ariz.
American Smelting & Refining Co., 120 Broadway, New York, N. Y.

Only 2 of these firms operated mines chiefly for molybdenum, 6 recovered molybdenum as a byproduct from copper ores, and 1 recovered molybdenum as a byproduct from tungsten ores.

MINES

Only the Climax mine of Climax Molybdenum Co. in Colorado and the Questa mine of Molybdenum Corporation of America in Taos County, N. Mex., are operated chiefly for molybdenum. Although the latter has been in continuous production since 1923, it has been a small producer, and ore reserves in 1955 were believed to have been very small and unimportant.

Climax Mine.—The Climax deposit, in Lake County, Colo., is by far the world's largest known molybdenum ore body. The deposit has a barren, conelike core above the Phillipson level that enlarges with depth, and the molybdenite content fades sharply out toward the core and fades out gradually toward the outer edge of the deposit.

According to Climax Molybdenum Co.:[5]

Ore reserves at Climax amount at present (1955) to some 330,000,000 tons. About three quarters of this tonnage is above our traditional commercial cutoff grade. The balance, although of somewhat lower grade, will be profitable. This tonnage should produce something like 1,600,000,000 pounds of molybdenum.

What are considered to be ore reserves is basically a function of the difference between the market price of the product and all costs of its extraction, treatment and sale. When this difference has been determined for ore of various grades, an appropriate cutoff grade can be selected below which mining is considered uneconomic. Material of a grade higher than cutoff constitutes ore reserves, while lower grade materials are not included or regarded as reserves.

This ore also contains small values of tungsten, pyrite, and tin, which are recovered as byproducts. These byproduct values are believed to be considered in determining the cutoff grade of ore; therefore, changes in the costs of recovering the byproducts and their market values might also affect the future economic reserve of the deposit.

Molybdenum production capacity is governed by the grade of headfeed and capacity of the milling and flotation sections. The grade of ore mined can be varied within wide limits by selective mining. The company now blends ore from the two mine levels to obtain a uniform headfeed. In 1956 the rougher circuit of the mill consisted of 15 separate units with a combined rated ore capacity of 32,000 tons per day. Another unit with a rated capacity of 4,000 tons per day was being installed and expected to be in operation early in 1957. This rated mill capacity can be varied rather widely in actual practice, depending on the fineness of the grind. A much larger ore tonnage could be milled daily by coarser grinding and the total

[5] Climax Molybdenum Co., Annual Report to the Stockholders: 1955, p. 4.

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amount of molybdenum recovered per day increased, but the result would be a decrease in overall recovery of the molybdenum content per ton of ore. This practice was followed during World War II, along with selective mining of higher grade ore, and the company materially increased its molybdenum output during that time. However, such a practice does not lend itself to conservation of the ore deposit or to the maximum feasible recovery of the molybdenum content of the ore mined. Finer grinding of the ore probably would increase the overall molybdenum recovery and might permit utilization of ore not now considered of commercial grade. This flexibility permits the company to adjust its molybdenum output up or down by perhaps several million pounds annually in response to demand.

During the years 1941–55, 56 percent of the estimated world supply and 63 percent of the United States production of molybdenum was derived from the Climax mine; however, the ratio between output from this mine and world supply and United States production in 1955 had increased to 64 and 70 percent, respectively.

BYPRODUCT

Since inauguration of the recovery of molybdenum as a byproduct from copper ores in 1936, this source has become increasingly important in the overall molybdenum supply. In 1955 approximately 30 percent of the United States production was derived as a byproduct from copper and tungsten ores. The relationship between molybdenum recovered as a byproduct and molybdenum mine output in the United States during 1936–55 is shown in figure 14 (p. 43).

Probably over a third of commercial molybdenum resources is in copper deposits where the ratio of copper to molybdenum ranges from perhaps 50:1 to 150:1. This ratio and resources are discussed in the section on Geology and Resources. Molybdenum was not being recovered from some of the copper deposits in 1955, and therefore there are opportunities to increase byproduct production, although probably at moderate additional costs.

Comparative data between production costs of byproduct molybdenum and molybdenum produced from mines in which it is the chief commercial product are not available. The difference in costs in producing molybdenum from the two sources may not be great because of the special flotation processes necessary to effect separation of molybdenite from the copper concentrate. The rather wide variation in molybdenite content of molybdenum-bearing copper ores may also cause costs of byproduct recovery to vary between deposits.

FOREIGN

CANADA

Although Canada has been an intermittent source of molybdenum since the early part of the 20th century, production has been small. In 1955 all molybdenum production in Canada, amounting to three-quarter million pounds, was derived from the Molybdenite Corporation of Canada, Ltd., La Corne mine in Quebec. This mine is operated chiefly for molybdenum; bismuth is recovered as a byproduct. Milling capacity was increased from 450 tons to 540 tons per day in 1955, and a further increase to 600 tons per day was scheduled for 1956, which would probably raise the annual molybdenum output to about 1 million pounds.

Ore reserves of the La Corne deposit are not believed to be large, but other molybdenum occurrences are known in many parts of Canada; some of them may prove to be economic.

CHILE

The only source of molybdenum in Chile through 1955 was that recovered as a byproduct of copper ore from the Braden Copper Co. El Teniente Copper mine near Sewell. This byproduct recovery, initiated in 1939, has made Chile the second largest producing country. Average annual production during 1950–55 was approximately 3 million pounds.

Early in 1956 The Anaconda Co. announced plans for recovering molybdenite from copper ores mined at Chuquicamata and at El Salvador (formerly Indio Muerto). Although the annual expected recovery of molybdenum from these copper ores has not been announced, it probably will be much more than that recovered from the El Teniente mine.

NORWAY

Most of Norway's molybdenum output has been derived from the Knaben mine. Molybdenum has been produced from this mine since the beginning of the molybdenum industry. Its production has never been large, and ore reserves are believed to be small and of low grade. No other molybdenum mines were being operated in Norway in 1956.

SECONDARY

Although molybdenum-bearing scrap is an important source of molybdenum, data on the quantity recovered are not available, and no comparison can therefore be made between primary and secondary supplies.

The major sources of secondary molybdenum are molybdenum-bearing high-speed steel scrap, low-alloy iron and steel scrap, and molybdenum metal scrap. High-speed steel scrap containing up to 9 percent molybdenum is commonly

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used in furnace charges at plants producing high-speed steels. Molybdenum-bearing, low-alloy iron and steel scrap normally contains less than 0.5 percent molybdenum; and although much of the scrap is added to alloy furnace charges, large tonnages are also used in carbon-steel furnace charges where the molybdenum content is diluted to a residual and lost to the secondary supply. Because of the comparatively small quantity of molybdenum metal produced, process scrap from this source has not been a major factor in the overall secondary supply, but it has been an important source of molybdenum for the production of high-temperature alloys.

Molybdenum-bearing, high-temperature alloy scrap probably will become an increasingly important secondary source of molybdenum as its use in these alloys increases. The Federal Bureau of Mines is investigating economic recovery of molybdenum and other alloying elements from high-temperature alloy scrap.

Only immediately after termination of World War I (1914–18) and World War II (1940–45) has the supply of secondary molybdenum contributed to the curtailment of primary production.

CAPABILITIES

About a third of the molybdenum supply is derived from copper mines, where production is primarily related to the supply and demand for copper rather than for molybdenum. Should the demand for copper remain high, byproduct output will doubtless continue at a steady pace; and, if demand for copper should drop, byproduct output of molybdenum would drop also. Therefore, short-run supply adjustments to meet changing market situations for molybdenum are largely limited to those mines that yield molybdenum as their chief product.

Since 1950 the ratio of byproduct production to direct mine production has decreased because of the large expansion programs at the Climax mine; but with research constantly improving molybdenite recovery at byproduct plants and with new byproduct producers entering the molybdenum supply, the relative contribution of byproduct molybdenum to total supply may tend to increase in the future.

Ability to expand production from both sources appears to assure an adequate supply of molybdenum for many years, except possibly war emergencies when abnormal quantities would be required. Such extraordinary requirements could probably be met through a stockpile program.

PRODUCTS

As virtually all molybdenite concentrates are converted to molybdenum trioxide, which is the raw material for a wide range of other products required by end users, the ability to manufacture these commodities is an important phase of the supply picture. The United States is by far the world's largest producer, and capacity to supply virtually all of the products is believed to be ample to meet peacetime needs. However, as demand for specific products increased rapidly, temporary shortages in production capacity developed, but industry quickly responded by increasing capacity. The principal firms manufacturing molybdenum products in the United States and some of the commodities produced are:

Molybdic oxide

Firm	Location of plant
Climax Molybdenum Co	Langeloth, Pa.
J. T. Baker Chemical Co	Phillipsburg, N. J.
Molybdenum Corporation of America.	Washington, Pa.
Republic Steel Corp	Canton, Ohio.
S. W. Shattuck Chemical Co	Denver, Colo.
Union Carbide Nuclear Co., a division of Union Carbide & Carbon Corp.	Bishop, Calif.
Miami Copper Co	Miami, Ariz.

Ferromolybdenum

Climax Molybdenum Co	Langeloth, Pa.
Molybdenum Corporation of America.	Washington, Pa.

Molybdenum metal

Climax Molybdenum Co	Langeloth, Pa.
Electro Metallurgical Co., a division of Union Carbide & Carbon Corp.	Niagara Falls, N. Y.
Fansteel Metallurgical Corp.	North Chicago, Ill.
General Electric Co	Cleveland, Ohio.
North American Philips Co., Inc.	Lewiston, Maine.
Westinghouse Electric Corp	Bloomfield, N. J.
Molybdenum Corporation of America.	Washington, Pa.

Ammonium molybdate

Climax Molybdenum Co	Langeloth, Pa.
General Chemical Division, Allied Chemical & Dye Corp.	Marcus Hook, Pa.
General Electric Co	Cleveland, Ohio.
J. T. Baker Chemical Co	Phillipsburg, N. J.
Molybdenum Corporation of America.	York, Pa.
S. W. Shattuck Chemical Co	Denver, Colo.
Westinghouse Electric Corp	Bloomfield, N. J.

Sodium molybdate

Climax Molybdenum Co	Langeloth, Pa.
General Chemical Division, Allied Chemical & Dye Corp.	Marcus Hook, Pa.
J. T. Baker Chemical Co	Phillipsburg, N. J.
Molybdenum Corporation of America.	York, Pa.
The Hilton Davis Chemical Co. Division, Sterling Drug, Inc.	Denver, Colo.
S. W. Shattuck Chemical Co	Cincinnati, Ohio.

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Foreign producers of molybdenum products depend largely on imports of concentrate to meet their needs. Some of these firms follow:

Gebr. Boehler
Kapfenberg, Styria, Austria

Metallwerke Plansee
Reutte, Tyrol, Austria

High Speed Steel Alloys, Ltd.
Widnes, Lancashire, England

Minworth Metals, Ltd.
Birmingham, England

Murex, Ltd.
Rainham, Essex, England

Badische Wolframerz-Gesellschaft m. b. H.
Braden, Germany

Herman C. Starck
Gosler, Germany

Soc. P. Azioni Leghe e Metalli
Genoa, Italy

Tokyo Tungsten Co.
Aoto Works
Tokyo, Japan

Tokyo Shibura Electric Co.
Sunamachi Works
Tokyo, Japan

Aktiebolaget Ferrolegeringar
Trollhattan, Sweden

Gullspangs Elektrokemiski Aktiebolaget
Gullspangs, Sweden

DEMAND

World conditions, level of industrial activity, assurance of supply, research, and the price of molybdenum are factors in determining demand. Past demand reached peaks during emergencies and in time of high industrial activity. An adequate supply, coupled with research, led to molybdenum replacing in part other elements that were either in short supply or priced higher.

WARTIME

Because of greatly increased ferrous alloy production, higher alloy content, and interchangeability, demand for molybdenum during past war emergencies increased tremendously over peacetime demand. As shown in figure 2, United States molybdenum consumption in 1942 reached a high of over 56 million pounds and as related to alloy steel production was 4.89 pounds of molybdenum per ton of steel produced. The decreased quantity of molybdenum consumed per ton of alloy steel produced in 1943–44 probably was due to changes in the types of alloy steels produced and to a shortage in molybdenum supply that caused it use to be restricted.

The more favorable supply position of molybdenum than alloying elements, such as chromium, nickel, and tungsten, during World War II was a main factor in changing many of the alloy mixes to conserve those more critical elements. Development of the triple alloy steels and substitution of molybdenum for tungsten are discussed in the section on Forms, Properties, and Uses (p. 51).

Although the demand for molybdenum in nonferrous alloys, as metal, and in nonmetallic applications was comparatively small, it also increased as the element was used more extensively in electronics and in catalysts, pigments, and other applications to meet wartime requirements.

PEACETIME

Assurance of molybdenum supply, level of steel production, research, and the price of molybdenum have been factors in determining the peacetime demand for molybdenum.

Early in the 1920's, when a steady supply of molybdenum had been assured and research had determined that it was a comparatively cheap and effective alloying element, it was adopted for use in ferrous alloys for peacetime applications. From this beginning the peacetime demand for molybdenum as an alloying element grew rapidly, and by 1935 world demand for its use in ferrous alloys probably exceeded 10 million pounds. Continued research by Government and industry proved the value of molybdenum as a partial replacement for tungsten in high-speed tool steels and other special alloy steels. Following the close of World War II in 1945 these steels were widely accepted for peacetime uses. During 1946–49 the United States consumption of molybdenum averaged over 20 million pounds annually. It is estimated that about 90 percent of the molybdenum consumed during the postwar years 1946–55 was used in ferrous alloys. As given in table 13 (p. 58), molybenum-bearing alloy steels produced in the United States have increased from a low of 27 percent in 1947 to 43 percent in 1955 of the total alloy steels produced, other than stainless. Although this increase was partly due to the rearmament program, which got underway in 1950, the big increase in automotive production, where large quantities of molybdenum-bearing alloy steels are consumed, was also a major factor in raising the demand for the molybdenum steels.

The scarcity of tungsten during World War II (1940–45), which made it necessary to substitute molybdenum in part for tungsten in high-speed and other tool steels, was perhaps mostly responsible for its continued use in these steels during peacetime when the supply of tungsten became adequate. The experience gained in using molybdenum-type steels, which proved the value of molybdenum as a substitute for tungsten and its more favorable price, coupled with the comparative alloying effect of the two elements, caused the molybdenum-type high-speed steels to be widely accepted for

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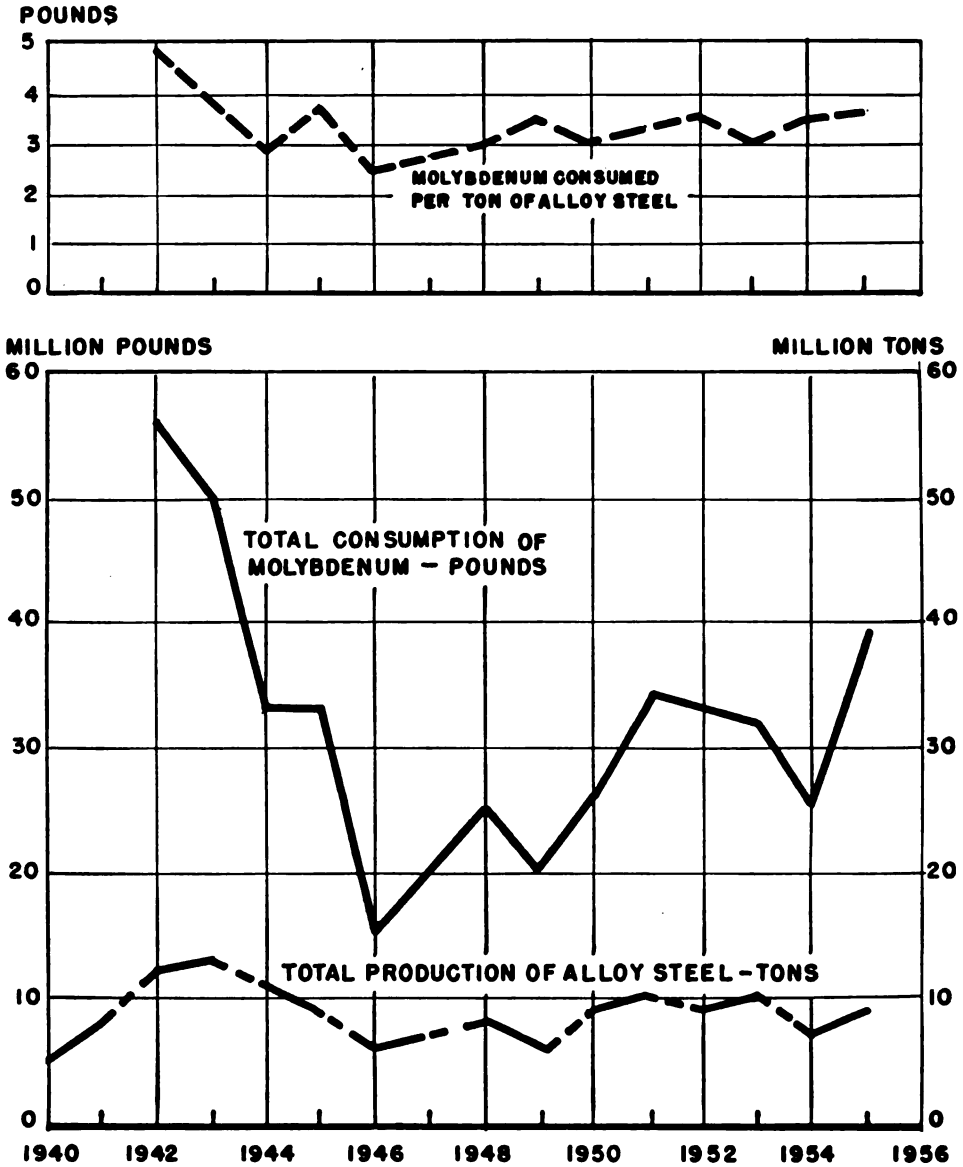

FIGURE 2.—Relationship Between United States Molybdenum Consumption and Alloy-Steel Production.

peacetime applications. The use of molybdenum-type high-speed steels in the United States during 1944–55 is given in table 14 (p. 59). Tungsten was again in short supply during 1950–53, and use controls in the United States required more extensive use of molybdenum-type high-speed steels. Even though these conditions have ceased, molybdenum probably will continue to replace tungsten to a large extent in these steels, as long as there is a wide spread between the price of the two elements. As shown in figure 3, the price of tungsten has fluctuated widely, while that of molybdenum has followed a uniform pattern and has been much cheaper.

FOREIGN

Foreign demand for molybdenum is largely met through imports from the United States. The small molybdenum production outside the United States has been erratic except for Norway and Chile. Table 16 (p. 65) gives the United States exports of molybdenum by countries; those from Chile and Norway are given in tables 18 (p. 68) and 19 (p. 68) respecively. As United States molybdenum exports indicate, demand by the Western European countries has increased significantly since World War II and doubtless will continue to increase as the standard of living in those countries improves.

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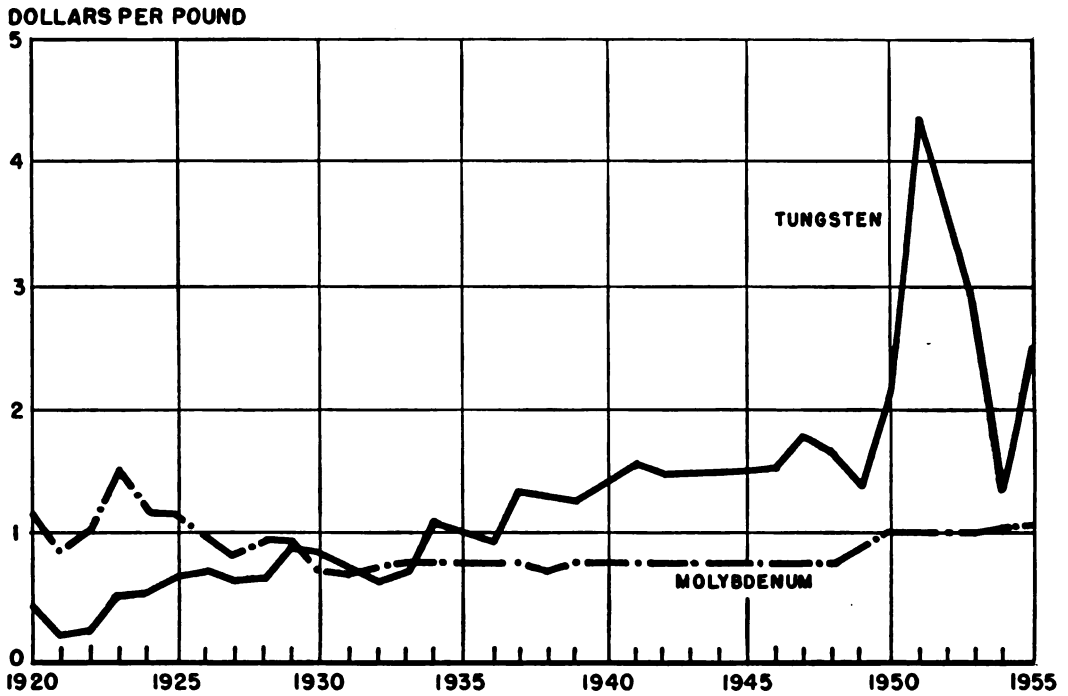

FIGURE 3.—Comparative Prices of Tungsten and Molybdenum Contained in Concentrate. (Tungsten prices include duty but exclude Government purchase price for domestic tungsten.)

Uses of molybdenum in foreign countries are estimated to follow closely those in the United States, and it is therefore believed that the main factors in governing demand are the level of steel production, the price of molybdenum, and the ease of obtaining dollars with which to purchase molybdenum by those countries. In the past, some countries have found that tungsten could be obtained with less strain on their economy, even though prices of the two elements favored molybdenum. This exchange problem was probably one reason for late adoption of molybdenum-bearing alloy steels by some of the European countries.

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MINING, BENEFICIATION, AND METALLURGY

MINING METHODS

There are four principal types of molybdenum-producing deposits: (1) Deposits that contain molybdenum alone or as the chief metal, (2) copper deposits that contain molybdenum recovered as a byproduct, (3) tungsten contact deposits that contain molybdenum recovered as a byproduct, and (4) wulfenite-bearing base-metal deposits. Only in the first type of deposit is the major mining effort directed toward the recovery of molybdenum.

Deposits that contain molybdenum alone or as the chief metal include quartz veins, pegmatites, stockworks, and zones of hydrothermal alteration related to porphyry stock intrusions.

Questa mine, Taos County, N. Mex., and La Corne mine, Quebec, Canada, are vein-type deposits mined by cut-and-fill stoping. The Climax mine, Lake County, Colo., is an excellent example of large-scale caving employed in massive, silicified, replacement ore bodies. Mining operations at both types of deposits are described in this section.

QUESTA MINE, NEW MEXICO

Mining methods of the Molybdenum Corporation of America at Questa, N. Mex., described by Carman (*13*) in 1931, are reported to have been used as late as 1955. This description is quoted in part.

HISTORY

This property, in the Red River Mining district, Taos County, northern New Mexico, was first recognized as a potential producer of molybdenum in 1916 or 1917. The R. & S. Molybdenum Mines Co. was organized in November 1918 by 2 men from Cripple Creek, Colo.; some ore was produced, which was milled at a gold mill on Red River about 5 miles above the mine. The Molybdenum Corporation of America was incorporated in 1920; in the same year it acquired the property and continued operations on a small scale. In 1923 construction of the present mill and camp site was begun. The mill began operating on November 1, 1923, and since that time the property has been a regular producer.

GEOLOGY

The ore occurs in a rock described as soda-potash alaskite porphyry. Molybdenite (MoS_2), the only mineral of economic value, occurs as a fissure filling in an east-west vein system. Quartz and some pyrite are the most important gangue minerals. The small branching quartz-sulfide veins are separated by altered, sericitized country rock; the vein filling actually comprises only a small proportion of the ground broken in mining.

MINING (13)

The molybdenite ore is mined from narrow, irregular veins * * * About nine-tenths of the ore mined is extracted by horizontal cut-and-fill stoping and one-tenth by open stoping. * * * Usually the ground requires the support given by filling. Other factors which may favor the cut-and-fill method are (1) the frequent necessity of breaking much more than the width of the ore to provide working room, in which case the resulting waste is most cheaply disposed of as stope fill and (2) the occasional very long tramming distance of waste from stope to surface.

Cut-and-Fill Stoping.—A cut-and-fill stope is started by taking a cut from the back of the drift and placing drift sets and lagging, and then building chutes. In this work an effort is usually made to avoid loading much ore or waste by hand, to avoid blasting directly down on unprotected timbering, and to place the waste fill as soon as possible in order to keep within working distance of the back. In some places, a 5- or 6-foot cut is taken from the back of the drift for a distance of perhaps 2 sets. This is loaded by hand into cars, and sets stood and lagged over. The next round is drilled and blasted so as to throw most of the ore over onto the timbering, where it can be sorted, and the ore dropped through the lagging into cars. Another set is then stood and the process repeated. In this way little hand loading is necessary and a fair covering of waste is left to protect the timbering when taking the next cut from the back. Another method of procedure is to break down a short 2- or 3-foot round from the entire length of the drift back to be included in the stope, then, working from on top of this broken material, drill a second round. Before shooting this, however, the first round is mucked out and timber stood. Then the second row is shot a few holes at a time and the broken ore sorted and dropped into cars below. The timbering under a stope is usually standard drift timber with single lagging overhead. In narrow stopes where the walls are good, stulls are occasionally used, or perhaps, half sets in which the hanging-wall end of the cap is supported on a post and the other end by a nitch on the footwall.

Chutes are next built at 50-foot intervals, with manways at every other one. If a stope is less than 50 feet long, only 1 chute may be required. The loading chutes are of 2-inch plank, with double-plank control gates held in cleats. The ore chutes and manways are carried up by cribbing or by setting stulls from wall to wall and lacing them on the outside with split lagging. In two-compartment raises the chute compartment is lined with plank on the manway side to prevent fine ore from running between the cribbing or lagging. The single-compartment chutes are usually about 3 feet square inside. The tonnage handled through stope chutes is very small, and the ore is not hard or abrasive. Consequently, the lightest construction that will safely hold the weight of the fill

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is permissible and economical. As all ore is worked over by hand in the stopes, no grizzlies are used over the tops of the raises.

Although ventilation or prospect raises are sometimes driven from level to level in ore and later made use of in stoping or may be driven for these purposes after stoping has started, no raises are driven from level to level for purely stoping purposes, such as travel ways or for lowering supplies into stopes * * *.

* * * * *

Various methods of breaking ore are used, depending on the ore occurrence and the ideas of the foreman and miners. * * * Where the ore is of sufficient width to give working room, and no breaking of the walls is necessary to fill the stope (that is, sufficient fill would be obtained by sorting), then the ore is broken down and the wall left untouched. If, as more commonly happens, the ore is not wide enough to provide working room, the practice is to break the footwall away from the ore, sort out of this waste such ore as has come down with it, then take down the ore exposed on the hanging wall. This can be done by picking or very light shooting. * * *

* * * * *

The ore is shoveled by hand into the chutes. If the distance to a chute is greater than usual, wheelbarrows may be used, but this it not necessary for the ordinary 50-foot spacing of chutes. * * *

* * * * *

Open Stopes.—Open stopes are usually small and are usually in flat-dipping veins. The method is often applied to ore which is known to be of slight extent or to ore whose extent is doubtful and where it is desired to explore in this way before installing chutes and regular drift timbering * * *

TRANSPORTATION

The ore is trammed to the surface and dumped into bins * * *. The cars on most levels are 12- or 14-cubic foot, box-body, end-dump type, weighing about 700 pounds and holding about 1,500 pounds of ore * * *. On two levels larger cars are used. * * * The hauls from stope to ore bin range from 200 to 1,000 feet * * *.

CLIMAX MINE

INTRODUCTION

The Climax Molybdenum Co. mine at Climax, Colo., with a 30,000-ton-of-ore-per-day record in 1955, is considered the largest underground mine in North America.

At an elevation of more than 11,000 feet the plant includes mine, mill, and a complete townsite.

The Climax method of caving is perhaps best characterized by its method of drawing ore from the caved area. Instead of drawing through grizzlies into storage or transfer chutes, the ore is brought directly into slusher drifts, whence it is loaded into cars by scrapers.

HISTORY

The Climax molybdenum mineralization was known before there was a market for the metal. The molybdenite was identified some time after 1900, but there was no production until 1918; owing to market conditions, the mine and mill were closed in March 1919 and remained closed until 1924.

Mining operations have progressed from the Leal level at 12,145 feet elevation downward to the White level at 11,940 feet, the Phillipson level at 11,470 feet, and the Storke level at 11,170 feet.

The original shrinkage-stope mining method produced up to 1,500 tons per day. Later additional ore was recovered from the pillars by large-scale blasting. Small coyote drifts and powder tees were driven in the pillars for emplacement of the explosive. The collapse of pillars and subsequent drawing of the ore from them indicated the feasibility of caving this ore.

In 1929 the Phillipson level was begun. Originally, the caved ore was drawn through finger raises onto grizzlies and transfer (or storage) chutes to the cars. Problems were encountered in using this method in ventilation, safety, communications, handling of men and materials, and maintenance. A slusher (or scraper) system of loading gradually evolved and has proved very successful.

DESCRIPTION OF DEPOSIT

The geology of the Climax deposit is discussed in another section (p. 11); however, a brief discussion here may aid in visualizing the mining operation.

Above the Phillipson level the deposit has the shape of a cone that enlarges with depth and has a barren central core. Thus, the Phillipson haulage level is roughly circular.

Foot wall and hanging wall are not clearly defined, and ore boundaries are determined by sampling. Mineralization decreases sharply toward the central core (foot wall) and gradually toward the outside periphery (hanging wall).

In the upper levels, the rocks are for the most part firm and fresh, and mining by block caving would be difficult if not impossible, except for the many closely spaced fractures that intersect the rocks.[6]

PROSPECTING AND EXPLORATION

Prospecting and exploration have been primarily by drifting and diamond (core) drilling. The total diamond drilling to 1955 was approximately 250,000 feet. In the early 1930's a 500-foot shaft was put down from the Phillipson level, and 500 feet of drift was driven at the bottom of the shaft to obtain water for the mill. During 1937 to 1940 nearly 3 miles of 5- by 7-foot drifting on this level was completed in addition to an extensive diamond-drilling program (*14*).

Because the mining method is by caving large areas, reliable information delineating the ore

[6] Vanderwilt, John W., and King, Robert V., Geology of the Climax Ore Body: Min. and Met., June 1946, p. 306.

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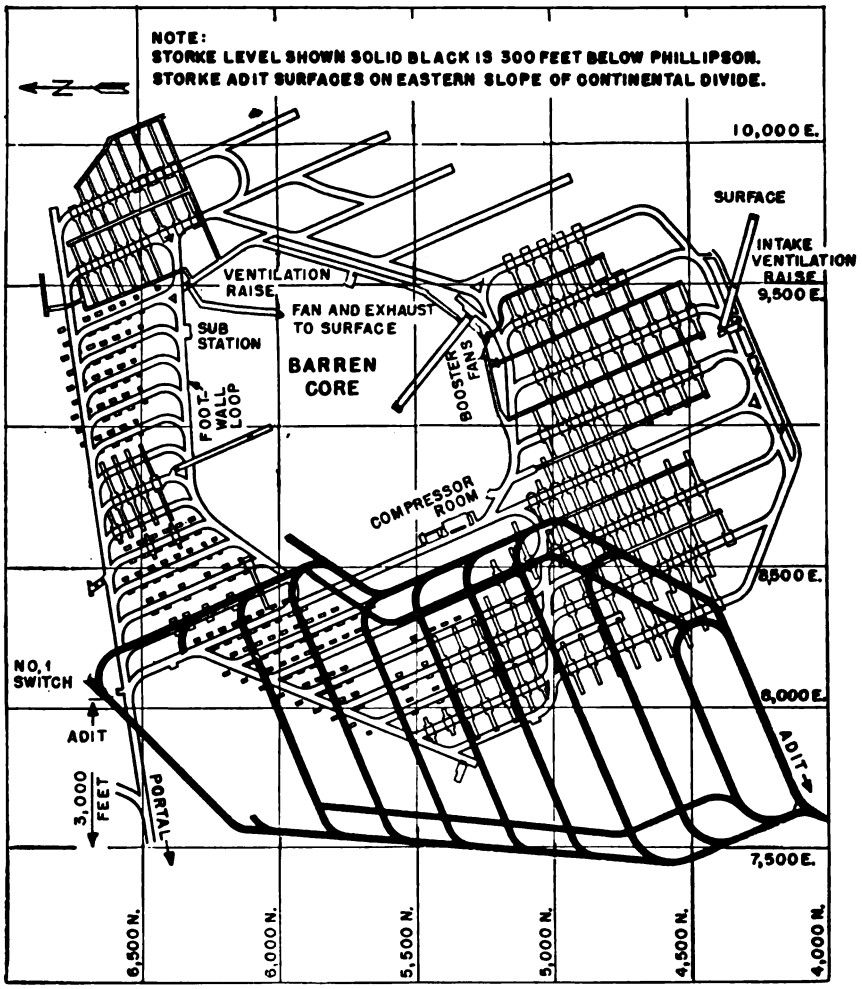

FIGURE 4.—General Plan of Phillipson and Storke Levels, Climax, Colo., Mine.
(Source: Mining Engineering, vol. 6, No. 3, March 1954, p. 275.)

body must be obtained by exploration. Diamond-drill core samples and faces of development excavations are analyzed and recorded. After production from an area is begun, the fingers are sampled daily, and samples are also taken from loaded mine cars. The remarkably uniform gradation of the ore allows these samples to be used in determining the remaining economic reserve of ore in the coring block.

DEVELOPMENT AND MINING

A plan view of the Phillipson level and a section of the Storke level are shown in figure 4. The progressive caving method of mining is based on the fact that, if a large enough area of a mine section is undercut, the weight of the ore will cause it to cave. The ore is of such a nature that, as it caves and is drawn, it will fracture to a size that works through the finger raises. Usual practice at Climax is to undercut a 68- by 100-foot area for individual stopes; however, since the stopes are adjacent, very large areas ultimately are undercut.

Before the ore is caved, facilities are installed to control its passage from the caved area to cars for haulage to the crusher. The caved ore comes down by gravity from the caved area through the finger raises to the slusher (scraper) drifts shown in figure 5. In the slusher drifts the ore is scraped directly into cars and hauled to the coarse-ore bins.

Loading.—After the preliminary development and stoping have been completed, the block begins to cave. The remaining portion of mining consists of loading, haulage, and maintenance. Loading combines the work of drawing ore from the finger raises and scraping it into cars. When conditions are favorable, ore comes down through the finger raises by gravity until it plugs the slusher drift. Then, as ore is scraped from the drift, more ore comes down. Various difficulties, however, interfere with the

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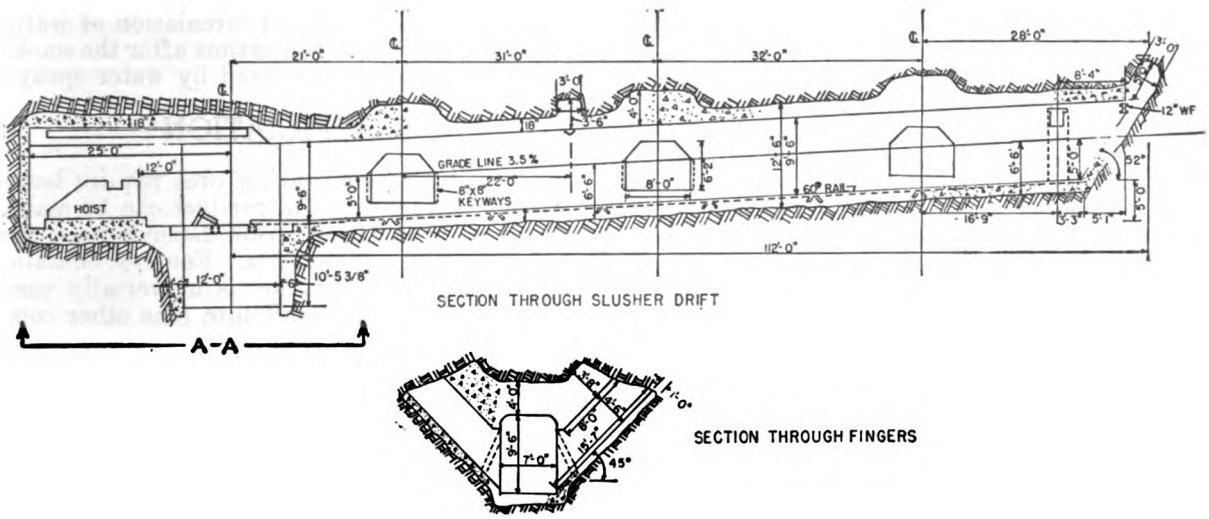

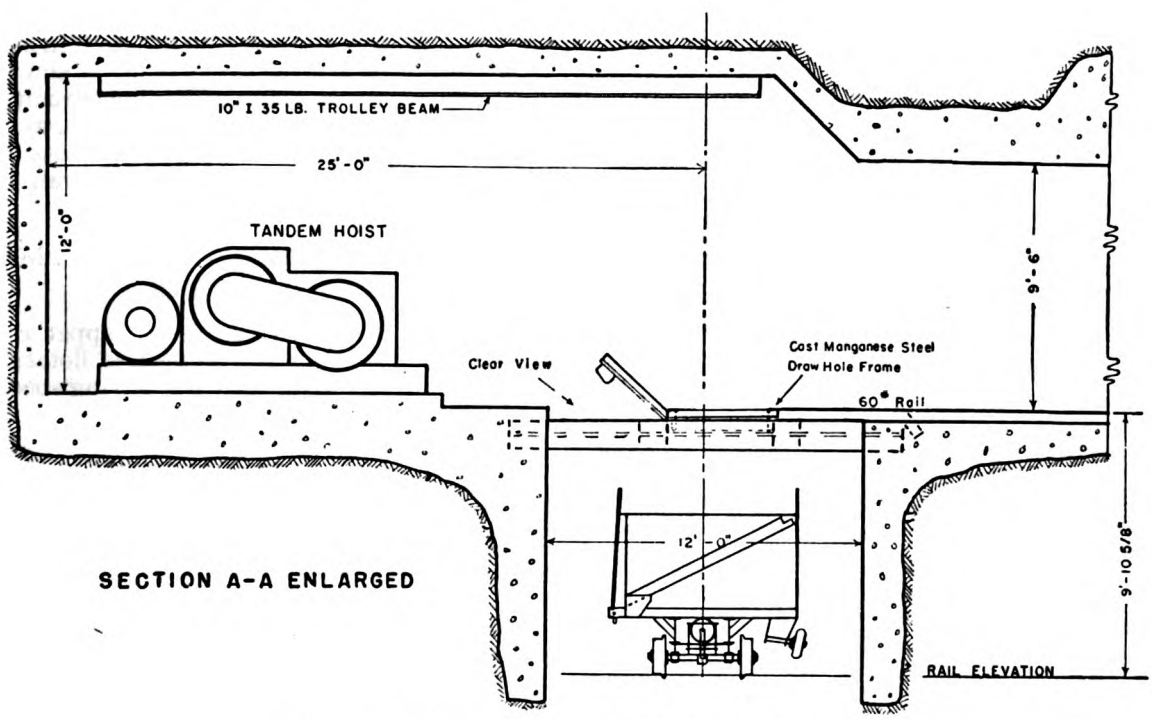

FIGURE 5.—Sketch of Slusher Drift, Climax, Colo., Mine.
Source: Mining Engineering, vol. 7, No. 8, August 1955, pp. 738–739.

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operation. Hangups are a major problem. These can be caused by fine material building up in the finger or by bridging of rocks or by massive chunks which may have come down. High-pressure water is provided, and frequently a hangup caused by the building up of fine material can be washed in. Long sticks of 2- by 1-inch cross section are employed to place dynamite where it will free a hangup effectively. Powder either in sticks or in a bag is tied to a wooden stick with twine. Thus, in most instances, the explosive can be wedged into place from the safety of the slusher drift. Infrequently it may be necessary to use hundreds of pounds of dynamite to free a single hangup.

Chimneys tend to form in the caved material, permitting barren material from above to work down through the ore. Such chimneys may be minimized by proper draw-point spacing, which, in turn, depends upon the coarseness of material to be drawn and by the use of careful draw over a large area.

Slusher drifts are constructed with 12 inches or more of concrete placed behind removable steel forms by means of a pumpcrete machine. Steel rails placed in the bottom prevent excessive wear from scraping. Visibility in the slusher drifts is good because of specially adapted sealed-beam lights and because ventilation openings to drifts at the far end pull dust and smoke away from the slusher operator. Large, double-drum 150-horsepower scraper hoists are used.

Tail-block beams are cemented in place in the back end of the slusher drifts. Seventy-two-inch scrapers developed at Climax are of the folding type. This is important because ore from the worn finger raises piles up against the back of the slusher drift, so that only a small opening is left for the scraper to pass through. Traveling away from the slusher operator, the scraper folds flat, but as it moves forward it opens to drag forward a load of ore.

Mine drainage is troublesome at times because of the large amount of surface water that drains through the caved ground when the snow melts. However, this is a seasonal occurrence, and 3-foot-square flumes in the bottom of the main haulageways have proved adequate.

Haulage.—Trains of 20 to 24 Granby-type 200-cubic-foot-capacity cars are hauled by 15- and 20-ton, 275-volt d. c. trolley locomotives. The track is 36-inch gage and ballasted. Sixty-five-pound and ninety-pound rail is used in the haulageways. Ventilation doors are operated by electric eyes, and a dispatcher controls traffic by means of derails, lights, and trolley phones. Ore is hauled directly to the ore bins, which are a short distance outside the portal at the elevation of the Phillipson level. Ore from the Storke level, 300 feet lower, is brought out through a tunnel to the crusher on the east side of the Continental Divide and elevated to the mill site by a conveyor belt 4,000 feet long.

Ventilation.—In handling a highly silicified ore, ventilation is of the greatest importance. The total circulation of air amounts to 1,600,000 c. f. m. and includes the recirculation of warm air, especially in the wintertime after the smoke and dust have been removed by water sprays.

BENEFICIATION

All molybdenum-bearing ores require beneficiation before a useful product can be made. The method of beneficiation depends upon the type of ore and impurities. For ores containing molybdenite, flotation is universally used for upgrading. No wulfenite (the other commercially important molybdenum mineral) is being produced at present. When produced it was beneficiated by gravity or flotation concentration.

Molybdenite is one of the most easily floated minerals, but when it constitutes only a minute percentage of the ore, such as in copper ores, where it ranges from about 0.01 to 0.1 percent, it is very difficult to separate the molybdenite from copper sulfide minerals and other impurities. This separation is made by what is known as preferential or selective flotation, which is accomplished by close control of the pH and the use of various reagents in the flotation circuit.

Several milling and flotation methods, along with flowsheets, as well as several patents for separating molybdenite from copper ores, are described in this section.

SEPARATION OF MOLYBDENITE FROM COPPER SULFIDES

Molybdenite is recovered from copper concentrate by preferential or selective flotation. The separation is complicated, requiring special treatment, as well as several flotation steps. Methods employed by the several producers vary.

The copper flotation concentrate, containing the molybdenite, may be first refloated with a depressant to keep down the molybdenite, along with some copper and iron sulfides and gangue material, producing copper concentrate and a tail product that is the rougher molybdenite product. In some processes this rougher product is roasted lightly to oxidize the surface of the copper sulfide particles and to drive off the reagents in preparation for further flotation treatment. In other processes the copper flotation concentrate containing the molybdenite is first treated by adding lime and steaming to retard the copper sulfide. In either method a rougher molybdenite concentrate is produced, leaving a copper-iron tailing.

The rougher molybdenite concentrate goes through several conditioning and reflotation

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steps, in which various reagents may be used to effect the preferential flotation.

MIAMI COPPER CO.

At Miami Copper, the copper concentrate containing the molybdenite is thickened and lime is added and heated to about 205° F. with live steam in a series of agitators for about 1 hour and 20 minutes to remove the collector film on the copper minerals. The product is then filtered and refloated, using mixed higher alcohols as frother and fuel-oil collector to separate molybdenite. The tailing (constituting the bulk of the copper) goes to the copper concentrator. The rougher molybdenite concentrate is flotation-cleaned about six times; the final concentrate is leached with sulfuric acid to remove the remaining copper, yielding a concentrate assaying 90 percent or more MoS_2.

KENNECOTT COPPER CORP.

Molybdenite is beneficiated at Utah Copper Division, Kennecott Copper Corp., as described in a communication from the company, as follows:

At the Utah Copper Division of Kennecott Copper Corp., recovery of molybdenite is accomplished in four flotation stages. A fifth stage embodying a cyanide leach is sometimes employed when it is desired to produce a molybdenite concentrate extremely low in copper content. Flotation cells are Fagergren, the plants containing both the Utah Copper and level cell types. Molybdenite in Utah ores floats readily, but its flotation rate is very close to that of the copper minerals with which it is associated (chalcopyrite, chalcocite, bornite). Therefore, to accomplish the difficult separation of the molybdenite from these copper minerals it was necessary to develop special techniques. Commercial production of molybdenite began in the early 1930's. The present process was developed in the laboratories at Utah and is covered by United States Patent Reissue 22,117 (Nokes, Johnson, and Janney).

In the first of the flotation stages mentioned above, the recovery of molybdenite from primary ore takes place. Actually it is the copper-flotation circuit, molybdenite being floated with the same reagents and together with the copper minerals. In recent years, molybdenite recoveries in this circuit have been improved by installing scavenger cells where a specific molybdenite collector is added. Product is a copper concentrate containing molybdenite.

The purpose of the second flotation circuit is to reduce the amount of concentrates to a reasonable figure for the subsequent treatment. This is accomplished by refloating the copper concentrate with the addition of a molybdenite depressant, which at Utah is dextrine. By this means, approximately four-fifths of the concentrate is floated in a molybdenite-impoverished product. The tailing is enriched in molybdenite although still containing some copper minerals.

Before treatment in the third flotation stage, the molybdenite-enriched tailing is filtered and the cake then passed through standard multiple hearth roaster. However, no roasting takes place, temperatures being carried at about 450° F. At this temperature, all of the reagents used in the copper circuit are destroyed, and, in addition, there is some tarnishing of copper minerals which aids in their depression in following stages. By careful control of temperature, there is no deleterious oxidation of molybdenite. Discharge from the roasters is repulped and then treated in the third flotation stage where an alcohol frother is the only reagent added. By this means, gangue insolubles which would later dilute the molybdenite concentrate are floated off. Following this treatment, the molybdenite is reactivated by the addition of fuel oil and treated in a normal flotation procedure using an alcohol frother. This stage involves multiple cleaning of concentrate and in order to insure concentrate with copper content low enough to meet the rigid specifications, a small roaster is installed about midway in the cleaning circuit. It is possible to produce molybdenite concentrate with copper content as low as two-tenths of 1 percent.

Figure 6 shows the molybdenite-recovery flowsheet.

The copper-recovery plant designated herein as the first flotation stage is not shown. The A circuit is that employing the dextrine sink, the B shows the insoluble float, and the units C and D are the fourth flotation stage, the D circuit being the cleaners.

PHELPS DODGE CORP.

At the Phelps Dodge Corp. Morenci mill the copper concentrate, containing molybdenite, is pumped to a conditioner where water is added for dilution and sulfuric acid for pH control. Ferrocyanide is added at the feed inlet to the first cell of each flotation bank. The rougher molybdenite concentrate is cleaned twice, thickened, filtered, and reground in a ball mill, followed by three or more cleaning stages in small Denver cells during which sodium cyanide and sulfuric acid are added.

BAGDAD COPPER CORP.

At Bagdad the copper concentrate, containing molybdenite, goes through a bulk flotation step, using a frother consisting of a 50–50 mixture by volume of pine oil and methyl alcohol to produce the rougher molybdenite concentrate, which is cleaned in 6 flotation steps.

UNITED STATES PATENTS

Several patents have been issued on processes for ore concentration by flotation for separating molybdenite and copper sulfides, using various reagents to effect the separation. Among the patents are:

U. S. Patent 2,492,936, issued to Charles M. Nokes, Charles G. Quigley, and Robert T. Pying on December 27, 1949, covers selective depression of metalliferous sulfides from molybdenite, using an inorganic compound selected from the group containing phosphorus, arsenic, and antimony, which contain bivalent sulfur and an inorganic cation.

U. S. Patent 2,187,930, issued to Earl H. Brown and Carl F. Williams on January 23, 1940, assigned to Minerals Separation North American Corp., New York, N. Y., covers depression of molybdenite from copper sulfides, using a depressant consisting of a condensation product of an aldehydic substance with aromatic

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sulfonic acids, or salts, of such a condensation product.

U. S. Patent 2,095,967, issued to Earl Henry Brown, October 19, 1937, assigned to Minerals Separation North American Corp., New York, N. Y., covers a flotation separation of molybdenite from copper sulfide, using a dye to selectively inhibit flotation of the molybdenite at a suitable pH while producing a copper sulfide flotation concentrate.

U. S. Patent 2,559,104, issued to Nathaniel Arbiter and Orel E. Young, July 3, 1951, assigned to Phelps Dodge Corp., New York, N. Y., covers the use of an oxidizing agent, such as sodium hypochlorite, under alkaline conditions, or potassium dichromate, under acid conditions, along with an activated carbon, to retard copper sulfides while floating molybdenite.

U. S. Patent 2,555,776, issued to Thomas A. Janney, Alpha G. Johnson, and Charles M. Nokes, September 16, 1941, covers separation of molybdenite from a mineral aggregate, including other sulfides, such as copper and iron sulfides, and gangue material by subjecting such a mineral aggregate to a heating treatment at a superatmospheric temperature in the presence of oxygen to effect oxidation of the other sulfides and then subjecting the aggregate so treated to froth flotation to recover the molybdenite therefrom.

U. S. Patent 2,664,199, issued to Lyle M. Barker and Orel E. Young, December 29, 1953, assigned to Phelps Dodge Corp., New York, N. Y., covers the use of a water-soluble iron cyanide, such as sodium ferrocyanide, under mildly alkaline conditions, followed by a final flotation with a water-soluble cyanide, such as sodium cyanide, under strongly alkaline conditions, to retard the copper sulfides. A detailed description of an example of this process follows:

Copper concentrate produced from the ore by an initial flotation using lime, organic thiophosphate, and a standard frothing agent as the reagents, containing a very low percentage of molybdenite, is passed into a conditioning tank where sulfuric acid is added to lower the pH to 7.0 to 8.0 and the pulp density adjusted to around 20-percent solids.

As the conditioned pulp is fed into the rougher flotation cells, about 0.33 pound of ferrocyanide per ton of original copper concentrate is added at the feed inlet of the first cell, which permits some flotation of copper and iron sulfides at the last flotation cell in each bank so as to obtain maximum flotation and recovery of the molybdenite. The flotation cells are the mechanical type, such as the standard Fagergren cells, and are connected in series.

The tailings from this rougher flotation contain most of the copper and after thickening and filtering are processed for the copper.

The rougher molybdenite concentrate is mixed with tailings from the fourth and final cleaning operations and goes to a thickener of the Dorr type to remove excess quantities of water containing frothing agents. The thickened material is fed into a second conditioning tank, where sulfuric acid is added to lower the pH to 7.0 to 8.0, and water is added to reduce the pulp density to about 14-percent total solids.

The pulp from this second conditioner is fed, along with a solution of sodium ferrocyanide amounting to approximately 0.24 pound of reagent per ton of original copper concentrate into another bank of flotation cells, where the first cleaning operation is performed. The concentrate from this first cleaning flotation is transferred to a third conditioning tank, and the tailings are recycled to the first conditioning tank.

In the third conditioning tank the pH is again adjusted with sulfuric acid to 7.0 to 8.0, and water is added to reduce the solids to about 10 percent. The pulp from this conditioning tank, along with about 0.071 pound of sodium ferrocyanide per ton of original copper concentrate, is fed into another bank of flotation cells; and, without further conditioning, the concentrate from this secondary flotation step goes directly into another bank of flotation cells, another portion of ferrocyanide having been added to the feed. The tailings from the secondary and tertiary cleaning operations are combined and returned to the second conditioning tank, and the concentrate is thickened and filtered in preparation for grinding in a ball mill.

The ground concentrate is diluted with water to about 2.5 percent of solids, and enough acid is added to adjust the pH range to 7.5 to 9.0, after addition of sodium ferrocyanide amounting to about 0.385 pound per ton of original copper concentrate, during introduction of the pulp into a bank of flotation cells, constituting the fourth cleaning stage. The tailing from the fourth cleaning stage is returned and mixed with the rougher concentrate going to the thickener preceding the first cleaner stage.

The concentrate from the fourth cleaner stage is passed directly, without any treatment or addition of reagents, to a bank of flotation cells constituting the fifth cleaner stage. The tailing from the fifth cleaning stage is recycled to constitute a part of the feed of the fourth cleaner stage, and the concentrate is ready for the final flotation cleaning.

The final flotation step consists of four cells, and in order to obtain maximum results from the sodium cyanide flotation is by countercurrent flow. The concentrate from the fifth cleaner flotation is added to the tailing being introduced to the cell next to the last cell. The concentrate produced in the last three cells is fed into the preceding cells, the sodium cyanide being added to the concentrate flowing into the first cell. The concentrate flowing from the first cell, containing 85 to 90 percent of molybdenite, is filtered, dried, and stored.

Figure 7 shows the general flowsheet of the process.

U. S. Patent 2,460,975, issued to Michael C. Carosella, February 8, 1949, assigned to the United States Vanadium Corp., covers a process for recovering molybdenum compounds from ore materials and aqueous solutions containing both molybdenum and tungsten compounds.

The process comprises the steps of adjusting the pH of an aqueous solution of molybdenum and tungsten compounds to a value between about 5 and 7.5, preferably between 5 and 7, by appropriate addition of a mineral acid or an alkali, and then adding to the solution a mineral acid salt of a divalent metal selected from the group consisting of iron, cobalt, nickel, and manganese. Under these conditions there is precipitated from the solution a molybdate of the selected metal, substantially free from tungsten compounds. To promote separation of the

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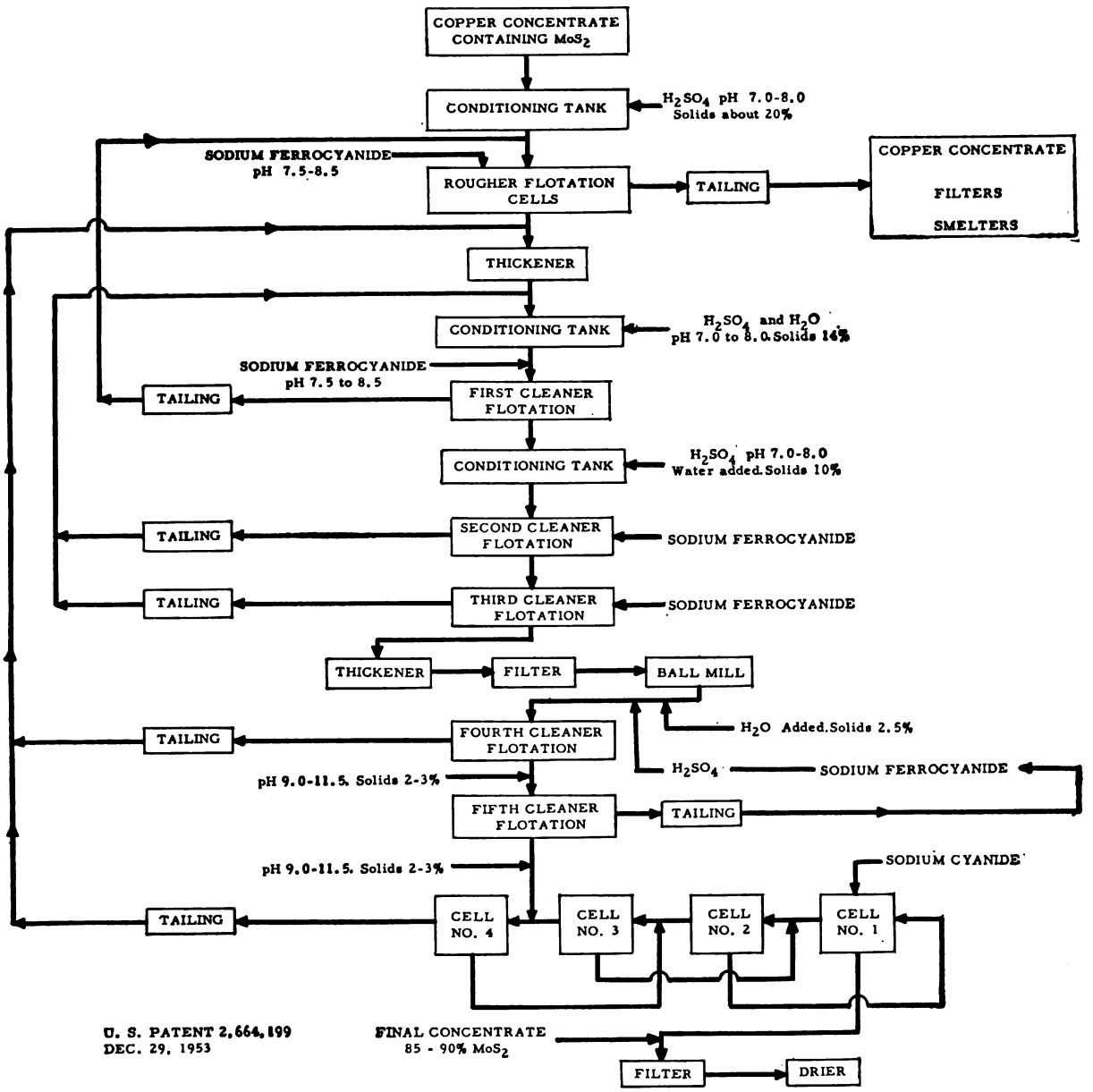

FIGURE 7.—Flotation Recovery of Molybdenite.

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molybdate from solution by filtration, the solution is heated to a temperature between about 75° C. and its boiling point during addition of the metal salt.

CONCENTRATION AT CLIMAX MOLYBDENUM CO.

The following description of the milling methods employed at Climax, Lake County, Colo., was obtained through the courtesy of Climax Molybdenum Co., as described by Dessor and Windolph:[7]

Milling operations at Climax started in 1918 with a 200-ton flotation plant. At that time the crusher was located at the mine and ore was delivered to the mill on a tramway. The plant closed down in March 1919 and remained closed until 1924, by which time a modest demand for molybdenum had been developed. From 1924 to 1932 the mill capacity was increased to 1,200 t. p. d., and mill sections added in 1932 increased capacity to 4,000 t. p. d. In 1936 and 1937, 6 additional mill sections were built, bringing the designed tonnage to 10,000 t. p. d. One more section was added in 1940. This together with improvements in grinding technique increased tonnage to 18,000 t. p. d. The most recent expansion program includes six more ball-mill sections and the Storke-level crusher. Present capacity is 28,000 t. p. d.

CRUSHING DONE IN THREE PLANTS

Crushing of Climax mine-run ore is carried out in three stages. No. 1 and 2 crushers are used for ore from the Phillipson level and No. 3 crusher treats ore from the Storke level. The flow of materials is the same in all three, but the third stage of crushing for the Storke-level crusher is done in No. 2 crusher.

Phillipson ore is dumped into the crusher bins from 10-ton-capacity Granby cars and fed to 48- by 60-inch Buchanan jaw crushers through chutes and Ross feeders. The jaw crushers have a discharge opening of approximately 9 in. and a capacity of 500 t. p. h. each. The product from these jaws is carried by pan and belt conveyors to a 5- by 9-foot vibrating grizzly with 1½-inch openings. The oversize is fed to 7-foot standard Symons cones, and the undersize joins the crushed material from the standard. The standard cone crushers are set at 1⅛ inches on the closed side and the product, all 3 inches, is fed to storage bins. Operating in closed circuit with vibrating screens; 7-foot shorthead Symons cones prepare the final mill feed, averaging 6 percent on ⅜-inch mesh.

STORKE-LEVEL CRUSHER DESIGNED TO HANDLE ALL FUTURE MINE PRODUCTION

The Storke-level crusher is designed to crush the entire mine production after the ore from the Phillipson level is depleted. The primary crusher at the Storke level is a 60-inch Nordberg gyratory.

Ore from the primary crusher is stored in a coarse-ore bin adjacent to the crusher building. From this bin the ore is fed on a 5- by 9-foot vibrating screen, with 2-inch openings. The oversize product from the screen is crushed in a 7-foot Symons standard cone and added to the screen undersize.

The product from Storke crusher is transported nearly 4,000 feet and elevated more than 300 feet to the fine-ore bins near No. 1 and 2 crushers. This conveyor system is divided into belts of nearly equal length operating 475 f. p. m. Designed capacity is 1,500 t. p. h. The ore from the fine-ore bin is delivered to the storage bins in No. 2 crusher for the final stage. The crushed ore from all 3 crushers goes to 14 cylindrical ore bins, 35 feet high and 35 feet diameter, having a capacity of 600 live tons of ore.

ROUGHER CIRCUIT

The rougher circuit consists of 14 units in parallel. Each unit is made up of a bin, ball mill, classifier, three 13-cell flotation machines, and auxiliary equipment such as feeder belts, pumps, and blowers.

There are eight 9- by 8-feet grate-type Marcy ball mills driven by a 450-hp. motor and six 9- by 9-foot grate-type Marcy ball mills driven by a 600-hp. motor. The use of shiplap liners is standard practice and 3-inch forged steel balls are charged daily. Consumption of balls is 1.30 lb. per ton of ore treated.

The classifiers are 78-inch Akins duplex high weir, with a double spiral. The first of these classifiers had 12-inch shafts, but recently completed installations have 16-inch shafts and it is felt that this increase in diameter will reduce shaft breakage. The circulating load is about 3 to 1.

Although several types of flotation machines have been tried, the standard equipment is the Weinig-Climax subaerated type. The power requirement for this machine is less than 1.0 kw.-hr. per ton and air at 1¾ p. s. i. is used at the rate of 35 c. f. m. per spindle. Normally the flotation circuit consists of three 13-cell flotation machines in series. The froth from the first machine is the rougher concentrate and the froth from the second and third machines is returned to the first. The reagents used in this circuit are:

Reagent:	*Lb. per ton*
Hydrocarbon	1.00
Syntex	.02
Pine oil	.05

CLEANER CIRCUIT

The rougher concentrate, containing 8 to 10 percent MoS_2, is thickened and then cleaned in 4 stages of flotation with grinding and classification between each stage. The first-stage grinding in the cleaner circuit is done with two 5- by 20-foot mills charged with ¾-inch forged-steel balls.

Second-stage grinding is done with two 8- by 20-foot mills charged with 2- to 3-inch flint pebbles. The final two stages of grinding use one 8- by 20-foot mill each, and the same pebble size as the second stage. The only reagents used in this circuit are small amounts of pine oil to promote molybdenite recovery, and soda ash with cyanide to depress the pyrite and chalcopyrite.

FILTERING AND DRYING

Concentrate from the cleaning plant is filtered in 6-foot Eimco disk filters, and dried in a 20-foot,4-hearth drier. The dried concentrate is either loaded in hopper cars or packaged in barrels.

BYPRODUCTS

Wolframite is the most important byproduct mineral recovered, but some cassiterite and pyrite are also recovered. These byproducts are recovered from the coarse tailing that originated in the rougher circuit.

Figure 8 shows a general flowsheet of the milling operations.

[7] Dessor, Max W., and Windolph, Frank, Crushing and Concentrating Ores at Climax: Min. Eng., vol. 7, No. 8, August 1955, p. 742.

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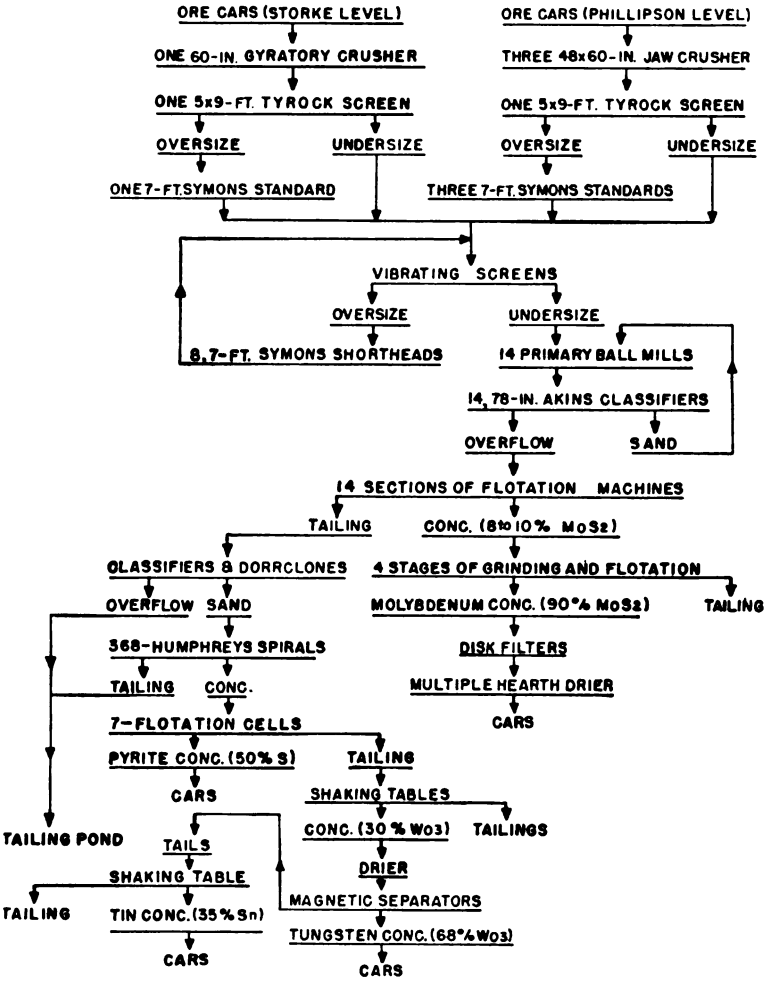

FIGURE 8.—Flowsheet of Molybdenum Plant, Climax, Colo.
(Data from Climax Molybdenum Co.)

UNION CARBIDE NUCLEAR CO., PINE CREEK MILL, CALIFORNIA

Ore from the Pine Creek mine in Inyo County, Calif., contains the molybdenum minerals molybdenite and powellite, an alteration product of molybdenite, along with the minerals chalcopyrite, covellite, chalcocite, bornite, and scheelite.

Recovery of molybdenum as a byproduct from tungsten-mining operations was started in 1939. Production reached a peak in 1943. The mill was shut down early in 1945, but operations were resumed in 1946 and have continued to date.

The mine ore is crushed in a cone crusher and ground in ball mills to 86 percent minus-325-mesh. The finely ground material passes through Akins classifiers, from where the overflow (containing about 55 percent of solids) goes to the sulfide roughers and the underflow is returned to the ball mills for regrinding.

The sulfide roughers, consisting of four identical sections in parallel, separate the sulfides as concentrate. The tailing from the sulfide roughers, containing the scheelite and some molybdenum minerals, goes to the scheelite roughers.

The sulfides are cleaned, thickened, filtered, and ground before entering the molybdenum roughers for final separation of the molybdenite and copper concentrates.

As mentioned above, tailing from the sulfide roughers contains the scheelite, along with some of the molybdenum minerals. This tailing passes through several cleaning and tabling operations before a final scheelite concentrate containing molybdenum is produced.

Figure 9 shows the general flowsheet of the plant.

Molybdenum and tungsten are separated by a chemical process (U. S. Patent 2,339,888, January 25, 1944), consisting of digesting the concentrate with an alkaline solution, such as caus-

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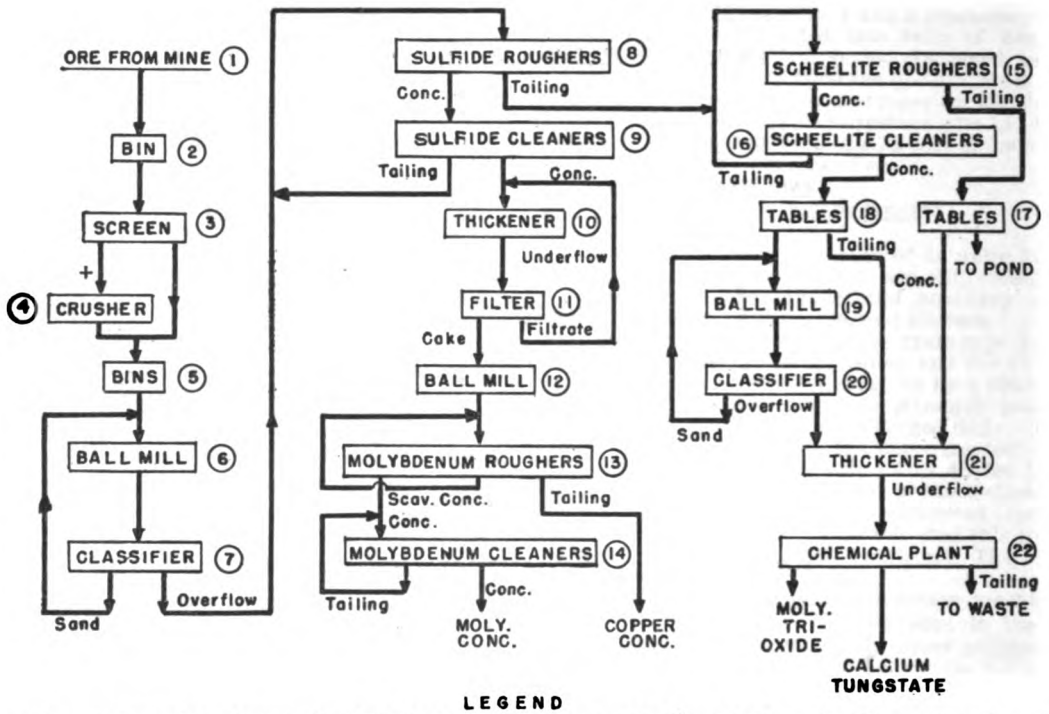

LEGEND

1. Minus-4-in. ore from mine primary crushing plant via aerial tram.
2. Wooden bin, 300-ton.
3. Symons vibrating screen, 32-in., rod-deck, 1/2-in. spacing.
4. Symons short-head cone, 5 1/2-ft.
5. Four 1,000-ton circular steel bins, or to stockpile. Capacity of fine crushing plant is 800 tons per shift.
6. Four 6- x 5-ft. Marcy low-discharge ball mills, 25 r.p.m., 7 1/2 tons 4-in. balls. Each mill grinds 250 tons per day to 86% minus-325-mesh. Ball consumption, 1 lb. per ton. Discharge, 70% solids.
7. Four Akins classifiers, 54-in., overflow at 55% solids.
8. Four identical rougher sections in parallel. Each has ten 32- x 32-in. M. S. cells, 8 for flotation and last 2 cells for conditioning scheelite flotation feed.
9. Four cleaner sections in parallel, five 32- x 32-in. M. S. machines in each. Two-stage cleaning; 3 cells in first, 2 cells in second. Sulfide concentrate has 20% MoS_2, 20% Cu, 30 oz. silver.
10. Thickener, 30-ft. diam.; pulp heated to 60° C., underflow diluted to 10% solids for filtration. Batch operation.
11. American filter 3-disk.
12. Ball mill, 36-in., filter cake ground at 70% solids.
13. Pulp at 20% solids to 2 banks, 6 cells each, 24- x 24-in. M. S. machines. First bank produces primary concentrate; second bank, scavenger concentrate.
14. Eight stages of cleaning in 16 24- x 24-in. M. S. cells, 2 cells to a stage. Tailing from each stage returns to previous stage; tailing of first stage returns to first bank in molybdenum roughers.
15. Four scheelite roughers in parallel; each has ten 32- x 32-in. M. S. cells. Each section "hog-troughed" by holes through cell partitions to form groups of 4-2-2-2 cells in each of the 4 sections.
16. Two-stage cleaning; five 32- x 32-in. M. S. cells in first, two 32- x 32-in. cells in second.
17. Four No. 6 Deister diagonal-deck tables recovering coarse scheelite from rougher tailings.
18. One No. 6 Deister diagonal-deck table recovering coarse scheelite from flotation concentrate.
19. Ball mill, 36-in.
20. Spiral classifier, 12-in.
21. Thickener, 30-ft., handles feed to chemical plant.
22. Chemical plant makes high-grade molybdenum and tungsten products.

FIGURE 9.—Flowsheet of Pine Creek Plant, California.
(Source: Engineering and Mining Journal, vol. 152, No. 5, May 1951, p. 82.)

tic soda, at about 130° C. for a long enough time for both molybdenum and tungsten to be dissolved; diluting with water; filtering; and precipitating the molybdenum as a sulfide that is filtered and roasted to molybdic oxide.

WULFENITE

The complex wulfenite-containing ores of the Mammoth district, Arizona, were treated by tabling and flotation. The Bureau of Mines investigated the concentration of these ores (*22*). The study indicated that all the Mammoth ores were amenable to flotation, although slightly less gold was recovered by flotation than by cyanidation. The Mammoth mill was equipped to handle 200 tons of ore per day by gravity concentration, flotation, and cyanidation; after several months' operation cyanidation was discontinued. Concentration by gravity and flotation methods resulted in considerable saving, both in operating cost and in added recovery of minerals. The mill was first owned by the Molybdenum Gold Mining Corp. but was sold in 1937 to Mammoth-St. Anthony, Ltd., and capacity was reported to have been increased to

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400 tons of ore a day. The Bureau of Mines[8] described the process used in separating the molybdenum contained in the concentrate as follows:

> Smelting in a reverberatory furnace of oxide concentrates (which have been mixed with soda ash and coke) yields a lead bullion containing the bulk of the gold and silver; a small amount of matte carrying lead, copper, gold, and silver; and a molybdenum-vanadium-rich slag, which is treated at the plant.
>
> The slag is hand-sledged, crushed, and ground wet in a rod mill. This solution contains the bulk of the vanadium and milybdenum that was in the slag. After suitable filtering, part of the solution is evaporated by smelter waste heat to the dry sodium molybdate-sodium vanadate salt; the remainder of the solution is used in the separation of the molybdenum from the vanadium.
>
> In the salt plant, the currently made salt, stored salt, and salt solution are mixed, the amount of stored salt to be used being determined from the specific gravity of the solution. This mixture is agitated for 8 hours. The molybdenum of the solid salt goes into solution, and the vanadium of the solution is precipitated. The product is filtered, the residue being the vanadium shipping product, which assays 20–25 percent V_2O_5 and less than 2 percent MoO_3. The filtrate is then agitated with lime and calcium chloride for 2 hours. This material is filtered. The residue is a low-grade molybdate-silicate precipitate, which is stored for future re-treatment. The filtrate is treated with calcium chloride, and a high-grade calcium molybdate is precipitated, filtered, dried, sacked, and shipped.

MILLING METHODS AT QUESTA, N. MEX.

Carman described the milling methods at the Questa concentrator of the Molybdenum Corporation of America, Questa, N. Mex., in a report (*14*) published by the Bureau of Mines in 1932. The same milling methods were reported to have been in use as late as 1955.

COARSE CRUSHING

Ore is transported from the mine to the concentrator by trucks and dumped into a bin which serves a 9- by 14-inch, belt-driven, Universal jaw crusher set at 1½-inch openings. A bar grizzly, with 1½-inch openings, is placed between the bin and crusher. The crusher product contains about 5 percent plus-1½-inch ring size and about 40 percent minus-½-inch ring size that joins the undersize of the grizzly and is delivered to a 100-ton-capacity fine-ore bin by a bucket elevator.

GRINDING

From the fine-ore bin the ore is delivered by conveyor belts to a No. 54 Marcy ball mill, which operates in closed circuit with a Dorr rake classifier and is driven at a speed of 27 r. p. m. through a friction clutch. The ball mill is equipped with a grate discharge that has 3/16-inch openings.

[8] Betz, Frederick, Jr., and van Sicien, Alice P., Molybdenum: Bureau of Mines Minerals Yearbook, 1942, p. 661.

The Dorr classifier, which operates in closed circuit with the Marcy ball mill, is set up at a slope of 2¾ inches per foot, and the rakes have a speed of 12 strokes per minute.

The launder used to convey the ball-mill discharge to the classifier has a slope of 1½ inches per foot, and the launder that returns classifier sands to the ball mill has a slope of 3¾ inches per foot.

Pulp density in the ball mill is maintained at about 80 percent and in the classifier at about 20 to 22 percent solids. The classifier is equiped with a hydrometer, installed at the overflow end, to assist in maintaining the desired pulp density.

FLOTATION

The classifier-overflow pulp is treated in a 7-pan 2- by 21-foot Callow rougher machine. The rougher machine produces a concentrate that is cleaned in 2 stages in 4-pan, 16-inch by 8-foot callow cells. These cells are equipped with 4-ply, ¾-inch, square, stitched blankets.

Air is supplied to all flotation cells at a pressure of 4 to 4½ pounds per square inch by a No. 2 belt-driven Root blower. The volume of air consumed amounts to about 800 to 900 c. f. m., which is equivalent to about 8 cu. ft. of free air per sq. ft. of blanket area per minute.

The flotation reagents used comprise Pensacola No. 100 pine oil, used as a collector; G. N. S. No. 5 pine oil, used as a frother; and sodium cyanide, used to depress pyrite. The pine oils are mixed in the proportion of 5 parts of Pensacola No. 100 to 1 part of the G. N. S. No. 5 by volume, and the mixture is added to the ball-mill scoop box at the rate of 1 pound per ton of ore. The sodium cyanide is added to the secondary cleaner as a 10-percent solution at the rate of 0.08 pound per ton of ore by a disk-and-cup-type feeder.

Sideboards are used on the two cleaner machines to force the froth to travel from the lower end to nearly the head before being discharged, in order to give a cleaner concentrate.

Metallurgical data for the flotation circuit are as follows:

Flotation-circuit metallurgical data

	MoS_2, percent
Rougher cell:	
Heads, not including middlings returned	5.2
Concentrate	30.0
Tailings	.9
Primary cleaner cell:	
Concentrate	55.0
Middlings	4.0
Secondary cleaner cell:	
Concentrate	74.5
Middlings	7.0
Scavenger cell:	
Concentrate	1 to 3
Tailings	.6
Recovery in final concentrate	87.7

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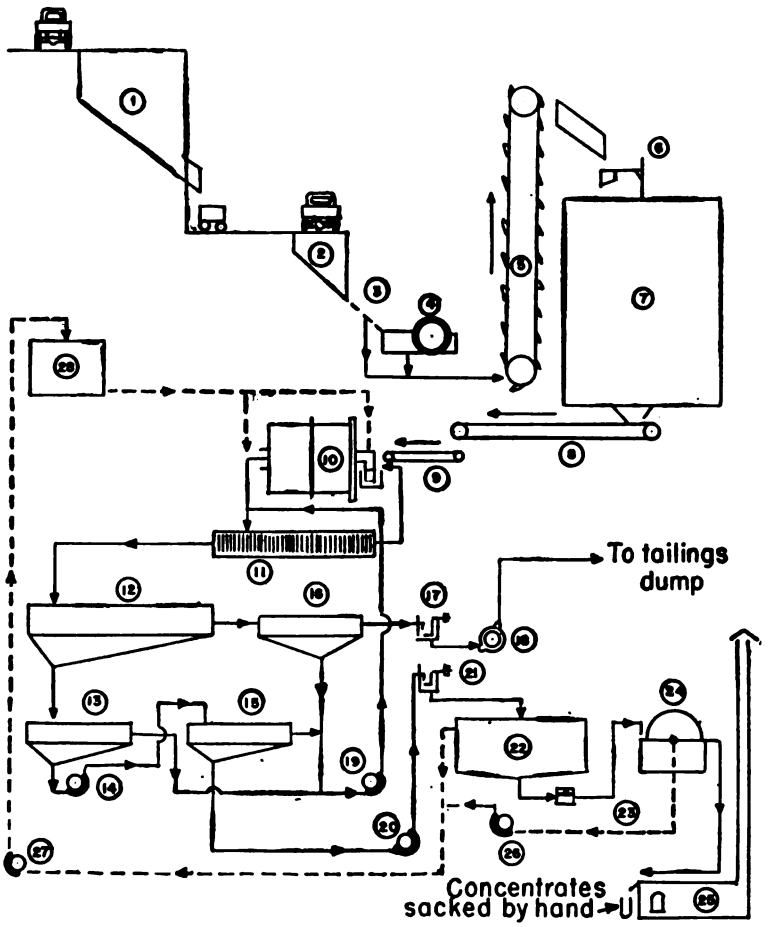

FIGURE 10.—Flowsheet of Ore Treatment at Questa, N. Mex. (*14*).

No. *Machines*

1. Reserve coarse-ore storage bin, 300-ton capacity.
2. Coarse-ore bin, 12-ton capacity.
3. Bar grizzly, 1½ inch openings.
4. Universal jaw crusher, 9- by 14-inch.
5. Bucket elevator.
6. Mechanical sampler.
7. Fine-ore storage bin, 100-ton capacity.
8. Belt conveyor, 20-inch.
9. Belt conveyor, 12-inch.
10. Marcy ball mill, No. 54.
11. Dorr Simplex classifier, 3 by 18 feet.
12. Callow rougher flotation machine, 2 by 21 feet.
13. Callow primary cleaner, 16-inch by 8-foot.
14. American centrifugal pump, 2-inch.
15. Callow secondary cleaner, 16-inch by 8-foot.
16. Callow scavenger, 16-inch by 8-foot.
17. Mechanical sampler.
18. Wilfley sand pump, 2 inches.
19. American centrifugal pump, 2-inch.
20. American centrifugal pump, 2-inch.
21. Mechanical sampler.
22. Dorr thickener, 14 by 18 feet.
23. Diaphragm pump.
24. American filter, 4-foot, single leaf.
25. Stove for drying concentrates.
26. Cameron centrifugal pump, 1-inch.
27. American centrifugal pump, 2-inch.
28. Storage tank for mill water.

The finished concentrate pulp of the secondary cleaner cells contains about 3 percent of solids and is pumped to a 14- by 8-foot Dorr thickener, which operates with a rake speed of 1 revolution in 8 minutes.

The thickener underflow pulp contains about 25 percent of solids and is further dewatered in a 4-foot, single-leaf American filter.

Vacuum at the filter is maintained at about 17 inches of mercury by an 8- by 5-inch vertical vacuum pump.

The filter cake, which contains about 10 to 12 percent of moisture, drops by gravity through a chute to a shelf adjacent to the drying stove. The concentrate is pulled off the drier by hoe and packaged for shipment.

DISPOSAL OF TAILINGS

The tailings pulp from the scavenger flotation cell is pumped to the tailings pond by a 2-inch Wilfley sand pump.

Figure 10 shows the general flowsheet of the mill.

LA CORNE MINE, QUEBEC, CANADA

HISTORY

Although molybdenite was discovered at the La Corne mine in La Corne Township, Quebec,

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in 1915, the first production was during 1927–30. The mine has produced intermittently since that time.

ORE

The ore occurs in veins and is complex, containing native bismuth and bismuthinite that make the separation of molybdenite difficult.

MINING

The mine has been opened on 6 levels through a 3-compartment, 61° inclined shaft. The first level is 150 feet vertically below the shaft collar, and the other levels are at 100-foot to 125-foot vertical intervals. Drifts and crosscuts are 6 by 7 feet in cross section and equipped with 18-inch-gage track. Shrinkage stoping is usually employed. The ore is hoisted by a 3- by 4-foot double-drum, 125-hp., Ingersoll-Rand shaft hoist.

MILLING

Crushing.—Mine ore is dumped from skips into a 250-ton coarse-ore bin. The single chute from this bin discharges into a short length of sorting belt, which also feeds the 15- by 24-inch jaw-type primary crusher. Secondary crushing is done in a 3-foot standard Symons cone, and all ore passing through ⅝- by 4-inch openings in a 5- by 10-foot Niagara screen goes to the mill ore bin. Grinding equipment consists of two ball mills—one 7- by 7-foot Dominion Engineering Co. cylindrical mill, 150-hp., 23 r. p. m., using 3½- and 4-inch balls, and a 7- by 6-foot Allis-Chalmers ball mill, with a 150-hp. motor in closed circuit with a single-rake classifier.

FLOTATION

The classifier overflow is conditioned and thence processed in a conventional bulk-flotation circuit, consisting of a unit cell and 2 primary cleaners, 24 scavenger cells, and 10 final cleaners.

The pulp is introduced at near-neutral and made slightly alkaline in the final cleaning. Flotation reagents and approximate quantities used per ton of float feed are summarized as follows:

	Pound
Aerofloat No. 25	0.017
Aerofloat No. 208	.060
Xanthate Z–6	.121
Dowfroth No. 250	.038
Sodium cyanide	.160
Sodium sulfite	.128

The molybdenite concentrate, containing bismuth minerals and other metallic impurities, is filtered in a 4-foot-diameter single-leaf American filter to about 12.5 percent of moisture. The filtered concentrate, containing about 81 percent of MoS_2, 6 percent of Bi, and 1 percent of Cu, goes to the leaching section of the mill.

Tailings normally contain less than 0.027 percent of MoS_2; 0.003 percent of Bi flows by gravity to an ample tailings-disposal area adjoining the mill.

Figure 11 shows the general flowsheet of the mill.

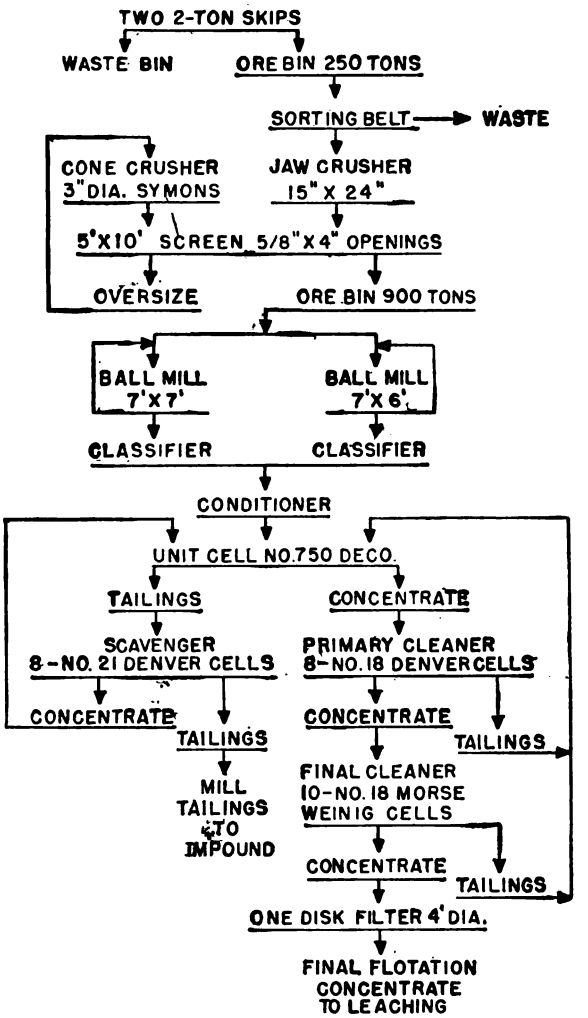

FIGURE 11.—Flowsheet of La Corne Plant, Quebec, Canada.

(Courtesy, Molybdenite Corporation of Canada, Ltd.)

LEACHING

Molybdenite flotation concentrate is acid-leached to recover bismuth and clean the molybdenite concentrate from contaminating impurities. Details of the leaching process are not available. After being leached and washed, the molybdenite concentrate is filtered, dried, and packed for shipment. The final concentrate contains over 90 percent of MoS_2 and less than 0.2 percent of Bi and Cu.

Recovery of both the molybdenite and bismuth is reported to be over 90 percent.

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Bismuth oxychloride recovered through the leaching process is mixed with coal, caustic soda, and salt cake and smelted in tilting-type, crucible, resistance furnaces.

METALLURGY

Virtually all molybdenite concentrate is roasted to technical-grade molybdic oxide (MoO_3), which in turn is the starting material for manufacturing most other molybdenum products.

CONVERSION PRACTICE AT LANGELOTH, PA.

ROASTING

The concentrate is roasted in Nichols-Herreshoff furnaces altered so that all hearths except the lower two are equipped with individual gas outlets connected to a common vertical header flue extending to the top of the roaster.

Preheating is done by natural-gas burners on alternate hearths, which are extinguished as the concentrate on the respective hearths becomes well ignited.

The concentrate is fed from a small hopper to one point on the perimeter of the top hearth by means of a screw conveyor. The shaft speed of the furnace varies with the charge from ⅜ to 1 r. p. m., to maintain the height of the ridges of ore at about 2½ inches. Rings with 8 small gas burners on each of the 2 hearths above the lowest assist in removal of sulfur from the roasted concentrate, which is discharged at 0.05 to 0.10 percent of sulfur.

Hearth temperatures are closely regulated by drawing a controlled quantity of air horizontally across them.

The gases pass from the vertical flue to a two-stage multiclave dust collector and then are exhausted into a 500-foot, brick-lined, concrete stack.

The roasted concentrate or molybdic oxide (MoO_3) is discharged from the furnace by gravity.

CALCIUM MOLYBDATE

Calcium molybdate is prepared by mechanically mixing an accurately weighted amount of roasted concentrate of known molybdenum content with enough pulverized limestone to give a product analyzing 46.3 to 46.6 percent of molybdenum.

MOLYBDIC OXIDE BRIQUETS

Roasted concentrate (molybdic oxide) of known molybdenum content is thoroughly mixed with air-floated pitch and elevated to a bin from where the mixture is fed by gravity to a 350-ton, fully automatic, hydraulic press. Four 4-inch-diameter briquets are formed per cycle of operation. The weight of each briquet is held constant within the limits of the accuracy of the briquetting operation, since the mix has a constant molybdenum content.

PURE MOLYBDIC OXIDE

Technical-grade oxide is fed in a thin layer to the sand hearth of a doughnut-type furnace. The hearth of the furnace moves under Globar heating elements operating at about 2,200° to 2,300° F., giving a hearth temperature of about 1,800° to 2,100°F. Air is drawn in over the heated surface and sweeps the MoO_3 vapors through ports in the outer perimeter of the furnace into a metal flue leading to a bag filter, where the pure MoO_3 is collected. The tailing, containing 45 to 50 percent of molybdenum, is discharged by means of a double-flight cutting and conveying screw and is suitable for use as raw material in other operations.

FERROMOLYBDENUM

Ferromolybdenum is produced by a silicothermite process. The reaction pot consists of a bottomless, brick-lined, steel shell set over a shallow pit of sand. When filled, a dust hood is set in place, the pot banked with sand, and the reaction started by igniting the charge with a starting fuse. Most of the fumes and dust are drawn off by fans to a bag filter.

A typical mix is 1,300 pounds of molybdenum as oxide, 1,200 pounds of ferrosilicon-aluminum (50 percent silicon, 10 percent aluminum), 800 pounds of high-grade iron ore, 80 pounds of limestone, 80 pounds of lime, and 60 pounds of high-grade fluorspar, which yields about 2,000 pounds of ferromolybdenum of 58- to 64-percent molybdenum content that is crushed to desired sizes.

MOLYBDENUM SILICIDE

Molybdenum silicide is produced in much the same way as ferromolybdenum. A typical mix for the production of molybdenum silicide is 1,000 pounds of molybdenum in oxide, 259 pounds of aluminum, 760 pounds of 90-percent ferrosilicon, 166 pounds of 50-percent ferrosilicon, 160 pounds of lime, and 50 pounds of high-grade fluorspar.

SODIUM MOLYBDATE

Sodium molybdate is produced by dissolving technical-grade molybdic oxide in a solution of caustic soda, filtering, evaporating, and drying.

Figure 12 shows the general flowsheet of the Climax Molybdenum Co. conversion plant at Langeloth, Pa.

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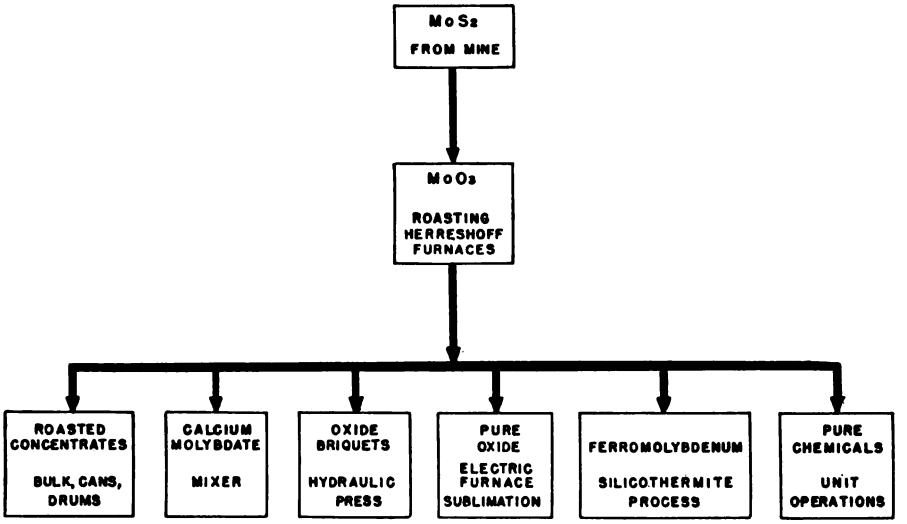

FIGURE 12.—Flowsheet of Conversion Plant at Langeloth, Pa.
(Source: Metals Technology, vol. 11, 1944, Tech. Pub. 1718, p. 3.)

CONVERSION PRACTICE AT WASHINGTON, PA.

Molybdenum Corporation of America, the world's second largest producer of molybdenum products, converts molybdenite concentrate to molybdic oxide in two 16-foot-diameter Nichols-Herreshoff roasting furnaces. One of the furnaces has 8 hearths, the other 10 hearths. The furnaces are operated on a heat gradient ranging from 300° F. on the first or drying hearth to a maximum of 1,250° F. on the roasting hearths. The furnace cycle from charge to discharge is approximately 4 hours. The sulfur content of the finished product ranges from about 0.06 percent to a maximum of 0.30 percent, depending upon the ultimate use of the oxide produced.

The finished molybdic oxide produced for shipment to the iron and steel industry is sampled as it comes from the roasting furnaces, stored in bins, and then packed in either cans or bags before shipment.

Bith high-carbon and low-carbon ferromolybdenum is produced at the Washington plant. High-carbon ferromolybdenum is produced in the electric furnace, and the aluminothermic process is employed in producting low-carbon ferromolybdenum. The electric furnace, approximately 60 inches high and 54 inches wide, takes a total charge of about 1,600 pounds, including reducing agents and necessary slagging materials, and yields 750 to 800 pounds of ferromolybdenum. Each heat requires approximately 3 hours. By the aluminothermic process about 600 pounds of low-carbon ferromolybdenum can be produced every 20 minutes, but because of the high cost of the reducing agents approximately 80 percent of the company's production is of the high-carbon, electric-furnace type. Some molybdic oxide is shipped to the company's York, Pa., plant for the production of ammonium molybdate, sodium molybdate, and pure molybdic oxide. Most of the pure molybdic oxide is processed further to metallic powder by carbon, natural gas, or hydrogen reduction, according to requirements.

PURE MOLYBDENUM TRIOXIDE

The pure molybdic oxide is prepared by sublimating technical-grade molybdic oxide or by calcining ammonium molybdate. It is also prepared chemically by precipitation with nitric acid. Sublimation begins at about 700° C., which makes it the preferred method of purification. Values of vapor pressure of pure molybdenum trioxide, calculated by K. K. Kelley (*21*), are:

Vapor pressure, atmosphere:	*Temperature, °K.*
0.0001	934
.001	999
.01	1,074
.1	1,207
.25	1,283
.5	1,350
1.0	1,424

The density of molybdenum trioxide varies according to the process used in preparation. The trioxide obtained by distillation has about half the density of the chemically precipitated substance.

CHEMICAL PROCESS

The chemical process or purification of molybdenum trioxide consists of dissolving roasted molybdenite in ammonia, filtering, and precipitating with nitric acid, which gives a relatively pure molybdic acid. The molybdic

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acid is ignited to molybdenum trioxide at a temperature below 1,000° C.

DISTILLATION PROCESS

The distillation process consists of heating roasted molybdenite in a current of air at about 1,000° to 1,100° C. and collecting the vaporized oxide in a filter bag. The process employed by Metallwerke Plansee, Reutte, Tyrol, Austria, is described as follows (*38*):

> Distillation units consist of quartz tubes in sheet-steel cases, mounted on trunnions, with gear for inclining the quartz tubes to any desired angle in relation to the collecting plant. The quartz tubes are wound with molybdenum wire, 1.5 mm. dia., which is afterward set in position with a thick slurry of fireclay. The space between the tube and metal case is filled with a mixture of fireclay paste and wood charcoal, the charcoal pieces being about 5 mm. dia. The object of the charcoal is to provide a reducing atmosphere of carbon monoxide for protection of the molybdenum wire winding. Incorporated in the sheet-steel casing is a large spring-loaded cover which acts as a gas-relief valve during heating up and when removed leaves a filling inlet for the fireclay-charcoal mixture.
>
> The quartz tubes are 15 cm. dia. and 60 cm. long, closed at the bottom with either a rounded or flat base. * * * The total diameter of a unit in its sheet-steel case is about 50 cm. and its total length about 80 cm.
>
> Each distillation unit is equipped for rotation and fitted with brush gear on the drive at the base for transmitting current to the windings around the quartz tube. * * * Units are normally inclined at an angle of 20° to the horizontal, the open end of the furnace being at the top; but they can be set at any angle by means of a lead screw in front of each unit. * * * The operating temperature of each furnace is 1,000° to 1,100° C. * * *.
>
> For collecting the molybdic oxide vapor there are 2 hoods over each unit; these are connected through exhaust fans to 2 collecting bags situated in a separate completely enclosed building. The collecting bags are 16 meters long and 1.5 meters diameter; they are made of a coarse, acid-resisting cloth known as "Loden." One collecting bag is for the initial distillates and the other for the pure product, which includes the redistilled product from the first bag. The distilling units are on rails so that they can be moved under either of the hoods.
>
> To start a unit it is heated up slowly with a cover over the mouth of the tube. After drying out thoroughly the cover is removed and a charge of 3 to 5 kilos is introduced. The temperature is slowly increased to 1,000°–1,100° C. while the unit is rotated and air is fed through an iron tube into the charge. The unit is operated under the first hood until about 100 grams of the charge has vaporized, when most of the impurities are considered to have been removed. It is then pushed under the second hood and distillation continued until the bulk of the volatile material has been released. A further charge is now added and the process repeated 4 or 5 times, after which the tube is brought to the horizontal position and the residues removed with a rake.

MOLYBDENUM METAL

HYDROGEN REDUCTION

Pure molybdenum trioxide (MoO_3) is the preferred raw material for reduction to metallic powder. The Metallwerke Plansee process (*38*) consists of reducing pure molybdenum trioxide in a hydrogen atmosphere that is carried out in 2 stages; the 2 furnaces, being of similar construction, have long muffles that are electrically heated by heating elements composed of molybdenum hairpin wire or rods supported from the top of the muffle. A sheet of molybdenum is fitted between the heating elements and the boats to prevent contamination. The purified hydrogen is dried by passing over solid potash.

The first reduction is carried out in mild-steel boats that hold about 10 to 15 pounds of oxide. The operating temperature in the furnace is 600° to 700° C., and 1 boat is fed about every 30 minutes.

The product from the first furnace is broken up and placed in nickel boats and fed at the rate of 1 about every 30 minutes into the second furnace, which is heated to about 1,000° to 1,100° C., after which the metal powder is screened and ready for processing into other metallic shapes.

A patented process[9] employs only one furnace in reducing molybdenum compounds, such as the trioxide or ammonium molybdate. The furnace for this process consists of a slightly inclined reduction tube of about 4 inches internal diameter, covered with a suitable insulating material enclosed in a sheet-metal envelop and heated by means of electrical resistance wires controlled by rheostats to provide 3 heating zones. Both the feeding and outlet ends of the reduction tube are equipped with water jackets for cooling. A reducing-gas inlet is provided at the outlet end of the reducing tube, an outlet for the excess gas and steam being provided at the feed end of the tube. Water inlets are available for each heating zone, and the ends of the tube are closed by hinged doors, the one at the feeding end being equipped with a mechanical pusher for moving the boats containing the molybdenum compound through the reducing tube. The reducing tube is made long enough to permit a given number of boats to be placed in the water-cooled section of the feeding end to insure operation of the furnace for a desired number of hours without shutting off the furnace for replenishing the supply of material to be reduced, and the lengths of the heating zones are made proportionate to the time during which the boats are to remain therein.

Operation of the furnace, using molybdenum trioxide (MoO_3) as a raw material, consists of placing about 2 kilograms of the trioxide in a metal boat (constructed of nickel or another refractory metal) and then putting the loaded boats in front of the mechanical pusher. Then the doors at both ends of the furnace are closed, water is circulated through the cooling jackets,

[9] Rennie, R. F. (assigned to Westinghouse Electric Corp.), Reduction of Molybdenum Compounds: U. S. Patent 2,491,210, Dec. 13, 1949.

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and hydrogen is turned on, flushing out the air in the tube to insure that no explosion occurs when the furnace is brought up to higher temperature. The desired temperature in the 3 heating zones of the furnace is then raised to about 400°, 630°, and 1,075° C., respectively, after which the flow of water to the heating zones is turned on and adjusted for desired dilution of the reducing gas. The mechanical pusher then moves the loaded boats through the various zones of the furnace at a rate of speed calculated to leave the boats in the first zone for about 1 hour, in the second zone for about 2¼ hours, and in the third zone for about 3½ hours.

The operation therefore starts at about 400° C. with the hydrogen diluted with a maximum amount of steam, which starts reduction of the molybdenum trioxide toward the lower oxidation product molybdenum dioxide, avoiding a runaway reaction.

The boats pass on to the second zone, where they are heated to about 630° C. in a reducing atmosphere more concentrated than in the first zone. Here the reduction to molybdenum dioxide is substantially completed, so that upon reaching the third or hottest zone, where the temperature is about 1,075° C., the still more concentrated reducing atmosphere does not cause a runaway reaction or development of imperfect metal.

FABRICATION

The high melting point of molybdenum and its affinity for oxygen make it difficult to convert the powder to ingot form.

Sintering.—Small ingots measuring about 2 by 2 by 16 inches are made by pressing the powder into shape in a hydraulic press and presintering in a hydrogen atmosphere at about 1,000° C. in order that they can be handled without much danger of breaking.

The presintered shape is sintered in a specially designed electric furnace by clamping vertically between two electrodes, the upper one being fixed and the lower floating in a mercury bath. The body of the furnace, which is movable, is lowered to its base, and the air is replaced with hydrogen. The electric current is passed through the bar or ingot and gradually raised until the ingot reaches approximately 2,400 ° C. The sintered ingot is then ready for hot swaging or forging and further processing into sheet, wire, etc.

Another process,[10] for producing ingots weighing 250 to 500 pounds, is based on a reversible oxidation reduction reaction between molybdenum powder and hydrogen-water vapor ($Mo+2H_2O=MoO_2+2H_2$). The process is carried out at temperatures well below the melting point of molybdenum but gives a dense mass, approximately equivalent in density and structure to melted molybdenum. The process consists of pressing the molybdenum powder into shape by hydraulic pressure and placing in a molybdenum boat where the pressed powder is supported by thin, transversely corrugated, molybdenum strips with the upper portions of the corrugations coated with a finely divided refractory powder to prevent welding during sintering. The corrugated molybdenum strips also prevent the pressed powder from welding to the boat and provide free circulation of the furnace atmosphere around the pressed powder during sintering. The charge is placed in a special-type electric furnace, and the furnace air is replaced with hydrogen saturated with water vapor, then the furnace temperature is gradually raised to 1,500°–1,700° C., at which temperatures the ingot is sintered.

Arc Melting.—Climax Molybdenum Co. developed a process for producing large ingots of around 1,000 pounds by arc melting under vacuum. The process requires a specially designed electric furnace in which an alternating-current arc operates between a vertical consumable electrode, made by extruding molybdenum powder through a special die fixed in the top of the furnace, and a pool of liquid metal. The electrode is partly sintered by resistance to the electrical current it carries into the arc. The lower arc-holding end of the electrode drips molybdenum into the pool below, held in a water-cooled copper cylinder, which serves both as the furnace bottom and the casting mold. The oxygen content of the ingot is controlled by adding a small amount of carbon.

MOLYBDENUM REFINING IN JAPAN

Molybdenum refining in Japan was described as follows (*42*):

Imported molybdenite concentrate or calcines obtained by roasting molybdenum concentrate to eliminate the sulfur are the usual raw materials for refineries. If the concentrate has not been roasted previously, it is generally roasted in gas-fired pan roasters at 600° to 700° C. for several hours until the sulfur has been oxidized and driven off.

The Horikawacho works of the Tokyo Shibaura Electric Co., Ltd., at Kawasaki, Kanagawa Prefecture, is the oldest molybdenum refinery in the country and has produced several times the tonnage of the next largest plant. This company obtained calcined concentrate made by roasting imported Korean concentrate from Awamura Mining Co., Ltd. A typical batch charge, to conform to the capacities of their equipment is 280 kg. of roasted concentrate containing 85 percent MoO_3, which is digested in a kettle for about 1.5 hours with 270 kg. of ammonium hydroxide having a specific gravity of 0.9 at 80° C. The residue, which contains 15.6 percent of molybdenum in the original charge, is thoroughly washed with water and stockpiled for future treatment. Molybdic acid is precipitated from the filtrate at 100° C. by adding 540 kg. of 1.35 sp. gr. nitric acid. Mother liquor from a subsequent crystallization step, which contains some molybdenum, is returned, and 1.3 percent of total molybdenum is recovered. The precipitate is water-washed by decan-

[10] Metal Industry, vol. 75, No. 20, November 1949, pp. 411–413.

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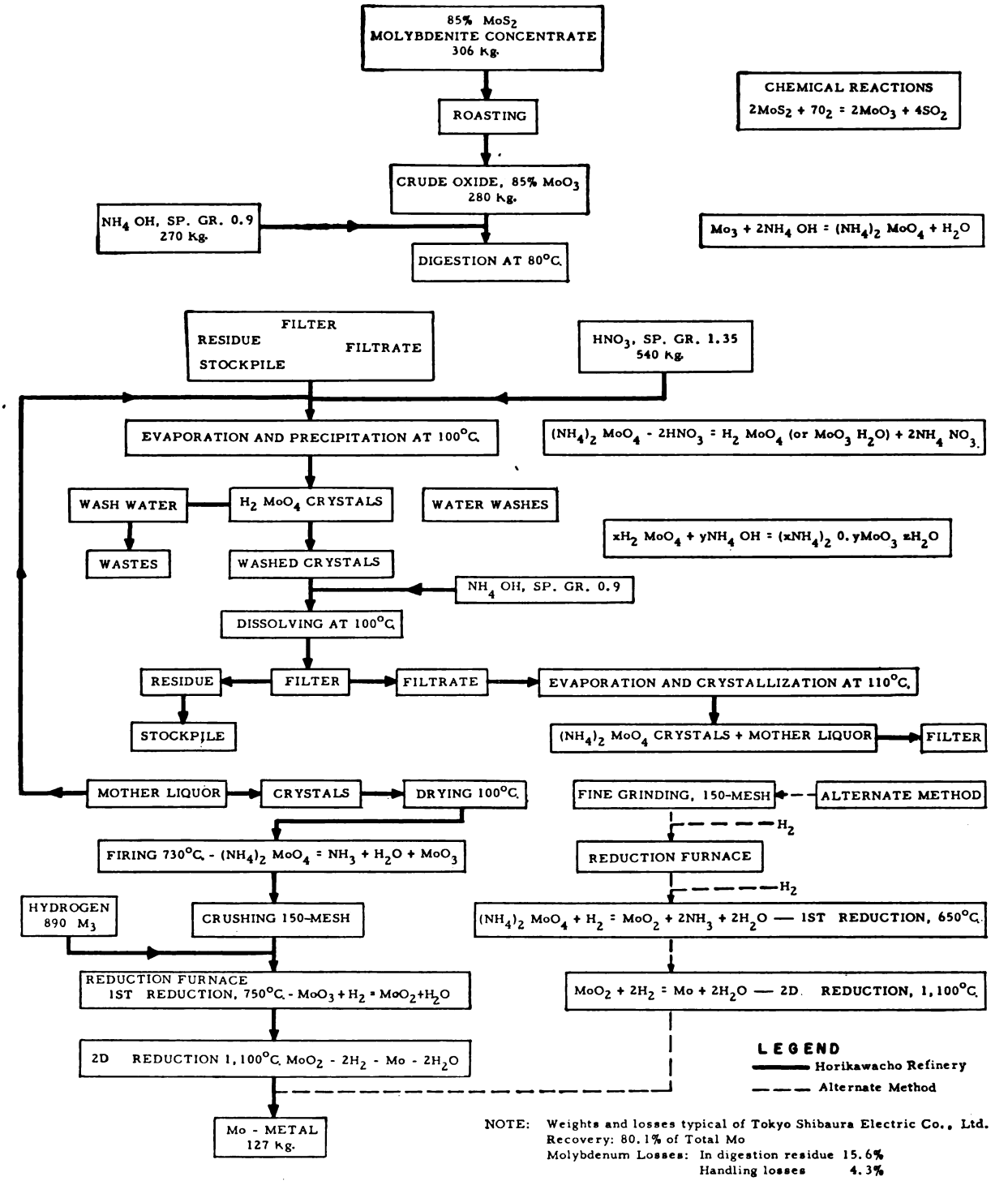

FIGURE 13.—Diagrammatic Composite Flowsheet for Refining Concentrate in Japan.

Source: Supreme Commander for the Allied Powers, Natural Resources Section, Tungsten and Molybdenum Metallurgy of Japan: Rept. 61, 1946, p. 16.

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tation; the wash water, containing 2.1 percent of molybdenum, is discarded. The molybdic acid precipitate is dissolved in 270 kg. of ammonium hydroxide solution having a specific gravity of 0.9, then filtered to remove any iron or alumina as hydroxides. The filter residue is rejected, causing a molybdenum loss of 0.6 percent. The clear ammonium molybdate filtrate is partly evaporated at 110° C. in casseroles yielding pure ammonium molybdate crystals and a small amount of mother liquor, which is separated from the crystals by filtering and returned to the process at the point where nitric acid is added. Handling losses during evaporation and filtration account for 1.8 percent of the total molybdenum. The crystals are dried at 100° C. for 24 hours and then charged into pans and placed in a homemade electric furnace, where ammonia is driven off at about 730° C. for 12 hours. The MoO_3, in lump form, is crushed to pass 150-mesh screen and charged into nickel boats of 1-kg. capacity for reduction in single-tube electric-resistance furnaces holding about 8 kg. each. Hydrogen manufactured by electrolyzing distilled water is passed through the tube to maintain a reducing hydrogen atmosphere while the oxide is being reduced to metal powder at a temperature of about 1,050° C. for 8 hours. About 900 $m.^3$ of hydrogen a ton is required. A loss of 1.1 percent results during the reduction operations owing to careless handling. About 127 kg. of metallic molybdenum powder is recovered that analyzes approximately 99.95 percent Mo. Overall recovery, which is 80.1 percent, could be improved materially by re-treating the residue from the first step where the calcined concentrate is digested with ammonium hydroxide.

In the past carbon was used as the reducing agent, but all plants changed to hydrogen, because it gives a purer product. Different plants vary their flowsheets to some extent from that of Tokyo Shibaura Electric Co., Ltd., but basically they are the same. The variation also is true of plant equipment, particularly of reduction electric furnaces, which are usually individually designed.

Figure 13 is a diagrammatic composite flowsheet of several plant practices in Japan.

MANUFACTURE OF FERROMOLYBDENUM

Ferromolybdenum may be produced in the electric furnace or by the thermite process.

In the electric-furnace process the raw materials may be: Molybdenite, MoS_2; molybdic oxide, MoO_3; calcium molybdate, $CaMoO_4$; or a sodium molybdate slag, Na_2MoO_4. The reducing agent is usually carbon, although 90-percent silicon material can also be used. Lime and fluorspar are used as fluxes.

When molybdenite is used as a raw material, about 100 parts of molybdenite to 58 parts of lime is necessary for slagging the sulfur as calcium sulfide, the reaction being: $2MoS_2+2CaO+3C \rightarrow 2Mo+2CaS+2CO+CS_2$. It is said that the reaction works close to the theoretical, and there is no difficulty in making a product with about 0.1 percent of sulfur and 1.5 to 3 percent of carbon. According to Eardley-Wilmot (*9*), Tivoni Electric Steel Co. of Canada manufactured ferromolybdenum by using molybdenite as a raw material in a single-phase electric furnace constructed of heavy boiler-plate, water-jacketed and lined with firebrick and silica brick. The charge consisted of 100 pounds of concentrate containing 75 percent molybdenite and 9 percent iron, 120 pounds of lime, 10 pounds of coke, and 5 pounds of steel scrap. The charge yielded a product containing 70 percent of molybdenum, 0.4 percent of sulfur, and 4 percent of carbon.

Reduction of molybdenite with silicon gives the following reaction: $MoS_2+Si \rightarrow Mo+SiS_2$. The reaction using sodium molybdate slag as a raw material and carbon for a reducing agent is $Na_2MoO_4+3C \rightarrow Mo+3Co+Na_2O$. The reduction of sodium molybdate slag requires considerably more power per pound of molybdenum produced than is required by the reduction of the oxide or sulfide.

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PRODUCTION

WORLD PRODUCTION OF ORE AND CONCENTRATE

HISTORY

Although the world contains innumerable deposits, mostly small, only a few countries have produced molybdenum in quantities adequate for their own needs. The Western Hemisphere, which has by far the most important molybdenum deposits in the world, has been the source of 87 percent of the total estimated world production.

Early production of molybdenum was spasmodic, starting in Norway before the element was identified, when it is said that the mineral molybdenite was used under the names of "silver stone" and "lead-pencil stone" as a lubricant and for polishing stoves. However, systematic mining did not start until about 1880 (*7*), when work at the Knaben mine in southern Norway was resumed. Production from this mine was irregular and small until about 1898. By the turn of the century, both Australia and the United States had joined Norway, but total production only amounted to a few tons annually. World War I created a heavy demand for molybdenum, which greatly stimulated exploration and development of molybdenum deposits in many parts of the world; the Climax deposit was developed during this time. However, at the close of World War I demand for newly mined molybdenum decreased because of large inventories at mines and industrial plants; the sharp break in prices that resulted made it necessary for United States producers to close their mines before the end of 1920. Norway and Canada also ceased to produce in the same year, but Australia continued to produce a few tons annually. Research launched to develop new peacetime uses for molybdenum began to show results before 1925 and was largely responsible for reopening of molybdenum mines in the United States and Norway.

Table 4, showing world production by countries, gives the producing countries and, for many, the quantities produced to date. The data for several of the producing countries are incomplete; in some instances, the molybdenum content was estimated from ore production.

Outstanding are the United States production, the almost continuous production of Norway, and the production of Chile since 1938, which has made that country the world's second largest producer.

PRODUCING COUNTRIES

UNITED STATES

The United States has the world's largest known molybdenite deposits. It also has a rather large aggregate of wulfenite ores in the Southwest from which a large part of the early production was derived. Serious attempts have been made to mine molybdenum in about a dozen States, but mine shipments have only been made from Arizona, California, Colorado, Nevada, New Mexico, Utah, Washington, and Wisconsin.

The first available data as to quantity output of molybdenum in the United States were for 1898, when 16,000 pounds of molybdenite concentrate assaying 42 to 56 percent of molybdenum mined in Arizona and New Mexico and 12 short tons of wulfenite concentrate assaying 90 percent $PhMoO_4$ were shipped from the Mammoth mine, Pinal County, Ariz. Small annual output, principally from Arizona, was made until 1906, when production ceased and was not resumed until 1914. In 1917 active exploration was begun by Climax Molybdenum Co. and the Molybdenum Products Corp, on different parts of the same large molybdenite deposit at Climax, Lake County, Colo., that were eventually to establish the United States as the world's premier producer of molybdenum. By the end of 1918 Climax Molybdenum Co. had a mill in operation with a capacity of 250 tons of ore per day. Meanwhile, the Primas Chemical Co. began developing the molybdenite deposit as Camp Urad on Red Mountain, Clear Creek County, Colo. As a consequence of these developments, the center of molybdenum production moved from Arizona to Colorado. The end of World War I brought about a sharp break in the market that made it necessary to suspend production at the Climax and Urad mines in 1919.

The mine of the Molybdenum Corporation of America, near Questa, Taos County, N. Mex., was opened in 1919 and made a small output in that year and in 1920, after which production was suspended until 1923. The mine has been a continuous producer since. Operations at the Climax mine were resumed in 1924; it has since been the world's major source of molybdenum.

In 1936 recovery of molybdenum as a by-product from copper ores was begun by the Utah Copper Division of the Kennecott Copper Corp. from the Bingham deposit in Utah. The

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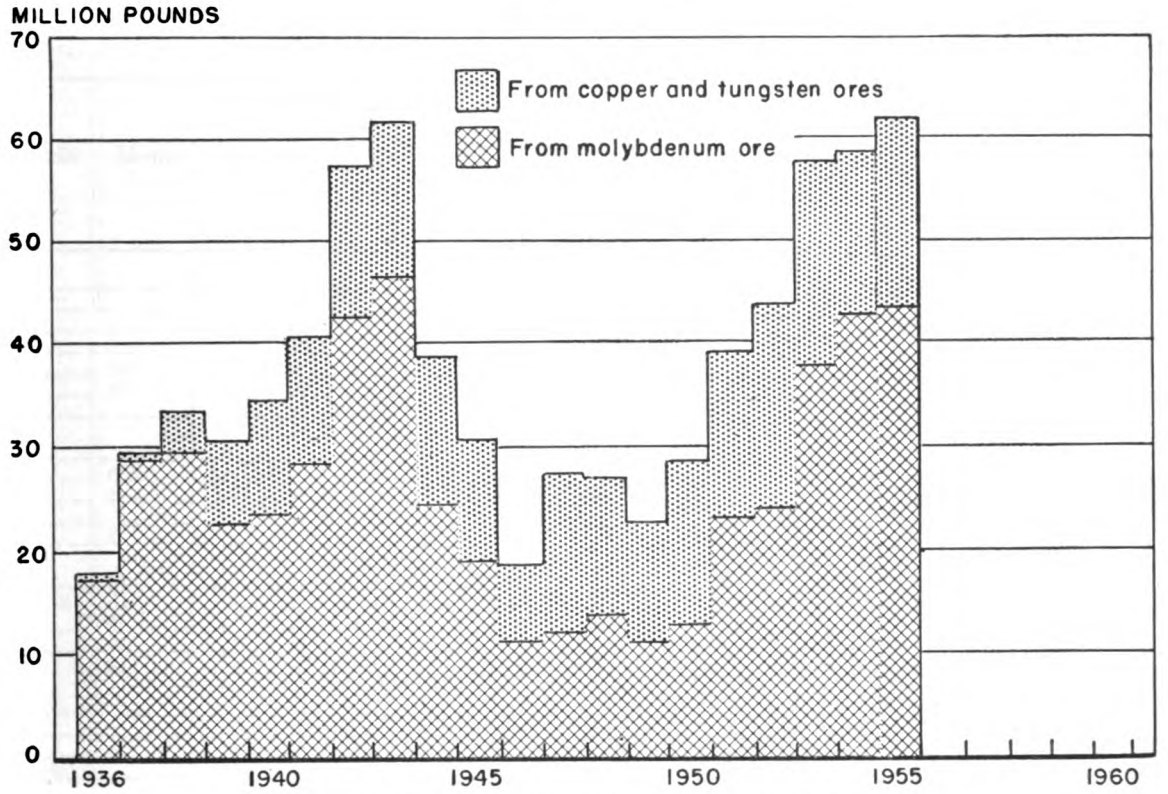

FIGURE 14.—United States Molybdenum Production.

following year the Nevada Consolidated Copper Corp., now the Chino Mines Division of the Kennecott Copper Corp., became a producer of molybdenum from the Chino copper property in New Mexico; in 1938 the Miami Copper Co. began recovering molybdenum as a byproduct from its copper operations at Miami, Ariz; in 1941 the Nevada Mines Division of the Kennecott Copper Corp. inaugurated recovery of molybdenum as a byproduct of its Ruth and Copper Flat operations and Custom Mines Corp.; in 1939 the United States Vanadium Co. (now Union Carbide Nuclear Co.) began recovering molybdenum as a byproduct from its tungsten operations at the Pine Creek mine in Inyo County, Calif.; in 1951 the Bagdad Copper Corp. began recovering molybdenum as a byproduct from its copper-mining operations at Bagdad, Ariz., and in the same year Phelps Dodge Corp. began recovering molybdenum as a byproduct from its copper-mining operations at Morenci, Ariz. Figure 14 shows the United States byproduct production of molybdenum compared with output from mines operated chiefly for molybdenum.

Production in 1943 was 61.6+ million pounds, of which over 46 million pounds was produced from the Climax mine, where selective mining was employed. This was a record high for the mine. Climax Molybdenum Co. had reserves of broken ore at the beginning of the war amounting to about 23 million tons containing over 150 million pounds of recoverable molybdenum. During the war this high-grade ore was depleted to about 9 million tons, and some unbroken high-grade reserves were also mined.

Following the close of World War II, Climax Molybdenum Co., having a large inventory of molybdenite concentrate, sharply curtailed production and converted part of the mill to a byproduct plant to recover tungsten, tin, pyrite, topaz, and monazite. As a result of this action and curtailed byproduct recovery, United States production hit a postwar low of only 18.2 million pounds of molybdenum in 1946.

In December 1950 Climax Molybdenum Co. entered into a Government contract designed to increase its production of molybdenum by expanding capacity, which included development of the Storke level of the Climax mine. In the succeeding years the company obtained another Government contract that also required further mill expansion and development of blocked-out ore which was largely a result of the Government molybdenum-expansion program calling for an increase of about 29.5 million pounds per year in addition to the total of 28.5 million pounds produced in 1950. The expansion goal was later revised to 70 million pounds per year.

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TABLE 4.—*World production of molybdenum in ore and concentrate, by countries,*[1] *through 1955, in thousand pounds*

Year [2]	Australia	Austria	Canada	Chile	China		Finland	Italy	Japan	Korea [3]
					Manchuria	Other Provinces				
Before 1905	203		(4)							
1905	93									
1906	127									
1907	99									
1908	110								86	
1909	137								11	
1910	187									
1911	137									
1912	179								209	
1913	163								4	
1914	170		2							
1915	148		18						7	
1916	150		95		4				18	
1917	216	33	174		4				18	
1918	227	26	227		2				9	
1919	216	29	51							
1920	99	24			[6] 22				117	
1921	18	51								
1922	[7] 73									
1923	82	66								
1924	66	86	11							
1925	49	18	15							9
1926	49	40	13							7
1927	(5)	(4)								33
1928	(5)	7								35
1929	(4)	7	18			9				33
1930	(5)	(4)				4				29
1931	(4)									26
1932	4					(4)				49
1933	9					(4)				117
1934	7					(4)			7	115
1935	13					[11] 4			9	117
1936	24					[11] 7		20	9	88
1937	73		9			[11] 13		2	4	93
1938	68		7		(5)	[11] 7		9	2	130
1939	86		(4)	66	(5)	[11] 7		4	37	882
1940	44		11	589	(5)	[11] 15	104	33	31	1,000
1941	13		104	505	[10] 165	[11] 11	326	40	42	866
1942	15	9	95	1,279	[10] 847	[11] 7	278	40	86	1,016
1943	31	11	392	1,499	[10] 1,138	(5)	238	20	185	1,021
1944	22	15	1,122	2,317	[10] 1,138	(5)	243	(4)	414	800
1945	(4)	(4)	503	1,854	[10] 66	(5)	203		209	342
1946	9	44	406	1,235	(5)	(5)	218		114	
1947	4	4	456	886	(5)	(5)	159		46	11
1948	4	4	183	1,173	(5)	(5)			2	4
1949	7	20		1,230	(5)	(5)				24
1950	7	40	62	2,187	(5)	(5)			29	
1951	(3)	42	229	3,803	(5)	(5)			119	11
1952	(4)	40	304	3,624	(5)	(5)			196	15
1953	(3)		194	3,031	(5)	(5)			397	20
1954	(3)		452	2,663	(5)	(5)			450	22
1955	(3)	(5)	774	2,817	(5)	(5)			439	24

[1] Molybdenum production in Bolivia, Burma, France, Germany, Hong Kong, Indochina, India, Greece, Rumania, and U. S. S. R. included in estimate for years in which production was made. Before 1931, world estimate includes production in Chile, Italy, and Peru. For 1946–54 estimate also includes North Korea and Spain for years in which production was made. Annual estimates are rounded and do not necessarily agree with the combined totals of the producing countries.

[2] This table incorporates a number of revisions of data published in previous Molybdenum chapters, Bureau of Mines Minerals Yearbook.

[3] Beginning 1946, South Korea only.

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TABLE 4.—*World production of molybdenum in ore and concentrate, by countries,*[1] *through 1955, in thousand pounds*—Continued

Mexico	Morocco, French	Norway	Peru	Spain	Sweden	United States	Yugoslavia	Total world	Years
----	----	115	----	----	----	282	----	600	Before 1905.
----	----	35	----	----	----	(5)	----	200	1905.
----	----	31	----	----	----	----	----	200	1906.
----	----	29	----	----	----	----	----	200	1907.
----	----	29	----	----	----	----	----	300	1908.
----	----	22	----	----	----	----	----	200	1909.
----	----	----	----	----	----	----	----	200	1910.
----	----	2	----	----	----	----	----	200	1911.
----	----	9	----	----	----	----	----	400	1912.
----	----	2	----	18	----	----	7	200	1913.
----	----	71	----	31	2	2	11	300	1914.
----	----	99	----	11	9	182	15	600	1915.
----	----	115	----	300	2	207	11	1,000	1916.
31	----	181	----	68	46	351	7	1,300	1917.
2	----	148	----	44	55	862	----	1,800	1918.
4	----	73	----	2	(4)	298	----	900	1919.
4	----	----	----	24	(4)	35	----	400	1920.
----	----	----	----	----	----	----	----	100	1921.
----	----	----	----	----	----	----	----	100	1922.
----	----	49	----	----	----	22	----	300	1923.
(8)	----	95	----	----	----	298	----	600	1924.
(8)	----	159	----	----	18	1,155	----	1,500	1925.
(8)	----	154	----	----	7	1,432	----	1,800	1926.
(8)	----	163	----	----	----	2,299	----	2,700	1927.
(8)	----	223	----	----	----	3,428	----	3,800	1928.
(8)	----	234	----	----	----	[9] 4,021	----	4,400	1929.
7	----	282	----	----	----	3,723	----	4,200	1930.
7	----	227	----	----	----	3,133	----	3,500	1931.
7	(8)	348	7	----	----	2,431	----	2,900	1932.
88	130	547	9	----	----	5,682	----	6,600	1933.
1,027	172	322	13	----	----	9,362	----	11,300	1934.
1,512	150	855	15	----	----	11,512	----	14,400	1935.
1,177	172	930	26	----	----	17,186	----	19,900	1936.
1,387	220	758	134	----	----	29,419	163	32,600	1937.
1,065	146	1,019	203	----	----	33,297	99	36,200	1938.
1,153	198	941	364	----	(8)	30,324	170	34,400	1939.
683	77	633	336	----	----	34,313	115	38,300	1940.
1,151	68	505	322	----	----	40,363	----	44,800	1941.
1,885	13	811	340	----	----	56,942	----	64,000	1942.
2,509	15	501	187	----	26	61,667	----	69,700	1943.
1,581	----	547	137	----	44	38,679	----	47,300	1944.
1,032	----	168	64	----	7	30,802	474	36,000	1945.
1,803	86	22	9	----	----	18,218	159	23,900	1946.
300	62	216	7	----	----	27,047	----	30,900	1947.
----	----	174	4	----	2	26,706	----	30,000	1948.
----	----	156	4	----	11	22,530	536	25,200	1949.
----	----	148	2	----	13	28,480	384	32,000	1950.
----	----	276	7	----	----	38,855	679	44,700	1951.
----	----	282	7	----	----	43,259	1,453	49,800	1952.
(4)	----	317	11	----	----	57,243	1,920	63,800	1953.
159	----	335	2	----	----	58,668	441	63,900	1954.
55	----	379	2	----	----	61,781	(8)	67,200	1955.

[4] Less than 1,000 pounds.
[5] Not reported separately; included with steel-hardening metals.
[6] Exports.
[7] 590 long tons of ore exported from Victoria not included.
[8] Data not available; estimate included in world total.
[9] In addition to the ore milled, a small quantity of ore averaging 16 percent MoS_2 was sold crude.
[10] Exports to Japan proper.
[11] Data represent areas designated as Free China during the period of Japanese occupation.

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TABLE 5.—*Salient statistics of molybdenum concentrate in the United States, 1939–55, in thousand pounds of molybdenum contained in concentrate*

Year	Production	Shipments (including exports)	Exports	Imports for consumption	Consumption	Stocks [1]
1939	30, 324	32, 415	[2]	26	[2]	[2]
1940	34, 313	25, 329	6, 585	----------	[2]	[2]
1941	40, 363	38, 377	7, 640	4	[3] 16, 891	21, 226
1942	56, 942	66, 437	11, 597	756	56, 388	12, 540
1943	61, 667	53, 955	10, 071	1, 572	49, 891	17, 993
1944	38, 679	39, 423	5, 985	2, 354	31, 520	19, 321
1945	30, 802	33, 683	2, 863	204	32, 696	16, 883
1946	18, 218	16, 787	565	[4]	14, 994	19, 275
1947	27, 047	22, 190	2, 989	----------	20, 221	23, 661
1948	26, 706	29, 669	4, 132	----------	25, 156	21, 206
1949	22, 530	23, 280	5, 320	48	19, 960	19, 159
1950	28, 480	44, 544	6, 235	3	26, 029	4, 326
1951	38, 855	37, 955	3, 729	4	33, 691	5, 058
1952	43, 259	42, 717	6, 172	50	32, 715	6, 856
1953	57, 243	53, 823	7, 037	----------	31, 193	11, 326
1954	58, 668	64, 775	13, 547	154	24, 710	5, 317
1955	61, 781	64, 467	14, 580	134	38, 799	2, 730

[1] At mines and at plants making molybdenum products.
[2] Data not available.
[3] 6 months, July to December.
[4] 10 pounds.

TABLE 6.—*Salient statistics of molybdenum products [1] in the United States, 1943–55, in pounds of contained molybdenum*

Year	Production	Shipments			Stocks (producers) end of year [2]
		To domestic consumers	Exports	Total	
1943	47, 982, 700	38, 865, 500	4, 571, 700	43, 437, 200	12, 176, 000
1944	30, 579, 800	31, 138, 500	1, 577, 500	32, 716, 000	6, 069, 000
1945	32, 406, 300	26, 977, 200	1, 327, 000	28, 304, 200	10, 176, 000
1946	15, 039, 100	16, 501, 700	442, 400	16, 944, 100	8, 211, 000
1947	20, 659, 700	19, 878, 500	866, 400	20, 744, 900	8, 126, 000
1948	24, 445, 300	23, 808, 900	1, 215, 800	25, 024, 700	7, 547, 000
1949	19, 624, 200	15, 019, 000	1, 314, 100	16, 333, 100	10, 838, 000
1950	25, 347, 800	32, 735, 700	1, 955, 100	34, 690, 800	1, 495, 000
1951	32, 775, 000	29, 845, 000	1, 387, 700	31, 232, 700	3, 037, 000
1952	32, 382, 600	30, 210, 700	1, 843, 600	32, 054, 300	3, 373, 000
1953	30, 283, 000	29, 595, 000	1, 107, 000	30, 701, 000	3, 894, 000
1954	24, 328, 000	23, 717, 000	1, 640, 000	25, 357, 000	3, 430, 000
1955	37, 774, 000	35, 935, 000	2, 671, 000	38, 606, 000	3, 156, 000

[1] Comprises ferromolybdenum, molybdic oxide, and molybdenum salts and metal.
[2] Reported by producers to the Bureau of Mines.

During 1954 Climax Molybdenum Co.'s expansion program was completed, and according to the company's Annual Report to the Stockholders [11]—

> The mine produced and the mill treated 8,709,900 tons of ore during 1954, an average of about 27,500 tons per working day. This was the largest production from any single underground mine in North America. Regular grade of ore was drawn approximately half from the Phillipson level and half from the Storke level. All low-grade ore was produced from the Phillipson level.

This development, along with increased by-product production due to improved selective flotation systems installed by some of the copper companies, resulted in the United States production reaching about 58.5 million pounds of molybdenum contained in concentrate in 1954. Mine shipments of molybdenum in concentrate during 1915–53 totaled 683,894,000 pounds, with Arizona supplying 2.81 percent, California 0.77 percent, Colorado 66.46 percent, Nevada 0.41 percent, New Mexico 3.58 percent, Utah 25.97 percent, and Washington and Wisconsin less than 0.1 percent combined.

Salient statistics for molybdenum concentrate in the United States are given in table 5, and table 6 supplies salient statistics on molybdenum products.

[11] Climax Molybdenum Co., Annual Report to the Stockholders: 1954, p. 3.

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ARIZONA

Arizona was the principal producer of molybdenum ores in the United States before 1918, when it was surpassed by Colorado. The production, mostly wulfenite, came largely from small mines. The old Mammoth mine at Shultz (about 40 miles north of Tucson), Mohawk, New Year, and Copper Creek properties were among the earlier sources of molybdenum in Arizona. Miami Copper Co., Bagdad Copper Corp., Phelps Dodge Corp., American Smelting & Refining Co., and San Manuel Copper Corp. recovered molybdenite from their copper-mining operations in 1956.

CALIFORNIA

In 1939 the United States Vanadium Co. began the byproduct recovery of molybdenum from its tungsten-mining operations at Pine Creek near Bishop, Inyo County. The molybdenum minerals in the ore are molybdenite and powellite. Some molybdenum concentrate was produced from small mines during World War I, but total shipments amounted to less than 4,000 pounds.

COLORADO

The largest output of molybdenum has come from the large deposit at Climax, Colo. The deposit is 13 miles northeast of Leadville at Fremont Pass. The altitude is 11,300 feet, and climatic conditions are severe. Snow can be expected during any month of the year. Winter generally sets in about November 1, and the ground remains covered with snow until about June; but, in spite of these severe climatic conditions and the relatively low-grade ore deposit, it has been developed into the world's largest source of molybdenum.

The Climax deposit was explored in 1917, and during 1918 a mill with a capacity for treating 250 tons of ore per day was installed. The mill was later enlarged to handle 1,000 tons of ore per day, but owing to lack of demand for molybdenum, it was shut down in 1919 after having produced concentrate containing a few hundred thousand pounds of molybdenum and was not reactivated until 1924. The mine and mill have been operated continuously since 1924; and capacity has been increased from the original 250 tons per day to 32,000 tons in 1956. Production rose to about 20,000 tons of ore per day in the World War II years and decreased to 5,000 tons per day in the first half of 1950.[12] At this time an expansion program was begun, and in 1955 daily production reached 30,000 tons.

[12] Climax Molybdenum Co., Annual Report to the Stockholders: 1950, p. 1.

On Red Mountain in Clear Creek County, about 35 miles northeast of Climax, is the Urad molybdenum mine. It was operated by Primas Chemical Co. in 1918 and later acquired by the Molybdenum Corporation of America. The mine was last operated in 1946, when about 200,000 pounds of molybdenum was produced.

NEVADA

The California Molybdenum Corp. developed the Shenandoah claim at Goodsprings and produced some wulfenite in 1935, but continuous production was not begun until 1941. At that time the Nevada Mines Division of the Kennecott Copper Corp. began to recover molybdenite as a byproduct of the McGill concentrator, where copper ores from the company Ruth and Copper Flat operations and from the Consolidated Coppermines Corp. Emma Nevada group are milled.

NEW MEXICO

As early as 1898 some molybdenum was produced in New Mexico. The Stephenson-Bennett mine at Oregon produced wulfenite in 1918. The Questa mine, Taos County, was opened in 1919 and since 1923 has been a regular producer. In 1937 the recovery of molybdenite as a byproduct of mining copper ore at the Chino mines was begun, and since 1939 the output of molybdenite from this operation has exceeded that at Questa.

UTAH

Except for several hundred pounds of molybdenum contained in molybdenite mined near Alta in 1916 and a few hundred pounds produced near Gold Hill in 1917, the output of molybdenum in Utah has come from the mining of copper ore at Bingham, where commercial recovery of molybdenite as a byproduct was inaugurated in 1936. Except in 1947, when it ranked first in production, Utah has been the second-ranking producing State since 1937.

WASHINGTON

In the latter part of the 19th century and the early part of the present century sporadic shipments of molybdenite were made from the Crown Point mine in Chelan County, the Castlemon mine in Whatcom County, and a property near Lucerne, Chelan County. The Deertail Monitor mines in Stevens County made small outputs between 1936 and 1941.

WISCONSIN

The only reported production of molybdenite in Wisconsin was in 1939, when 3 short tons of concentrate was produced at a property in Marinette County.

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FOREIGN COUNTRIES

AUSTRALIA

Australia began producing molybdenum concentrate before the beginning of the century and for a period before World War I was the world's leading producer. The country's production reached a peak in 1918, when concentrate containing about 227,000 pounds of molybdenum were produced. Production gradually declined for the next several years and has now virtually ceased, except for small quantities recovered as a byproduct in mining for wolframite, bismuth, or quartz crystals.

Molybdenite is the only molybdenum mineral of importance mined in Australia; but minor amounts of molybdite have been mined, and wulfenite from the Junction mine at Broken Hill, Queensland, has been recorded.

Although deposits of molybdenite in Queensland, New South Wales, and Victoria are numerous and scattered deposits are known in Tasmania and Western Australia, production has been small, and none has proved to have major importance. The Everton mine in Victoria, Wolfram Camp, and Bamford in the Chillagoe mining district of North Queensland and Kingsgate in New South Wales have yielded most of the country's molybdenum output.

Before 1941, when Broken Hill Pty. Co., Ltd., installed a furnace for producing ferromolybdenum, all of Australia's molybdenum production was exported, mainly to the United Kingdom.

CANADA

Molybdenite was first produced in Canada in 1886 (*9*), when a small quantity was sold for cabinet specimens. No further production was reported until 1902, when a small shipment of molybdenite ore mined in Laxton Township, Victoria County, Ontario, was made; however, production was negligible until World War I, during which time many occurrences and small deposits were explored in various parts of the Dominion.

The Moss mine, at Guyon, Onslow Township, Quebec, yielded about 80 percent of the total Canadian output during the World War I period and was at one time the world's largest producer, but the sudden fall in the molybdenum market in 1918 caused collapse of the Canadian molybdenite-mining industry. Very little production was reported during the next year; it ceased in 1920. No further production of molybdenite was reported until 1924, when a few tons was produced.

Although molybdenite was discovered in La Corne Township, Quebec, in 1915, no active development of the La Corne property occurred until 1927–30, when a shaft was sunk and a mill erected, but production ceased after only a few tons of molybdenite concentrate had been produced.

From 1943 to July 1945 the property was operated by a Crown company that produced 198,457 tons of ore, grading 0.67 percent MoS_2. In 1945 Molybdenite Corporation of Canada assumed control of the property and continued operations until December 1, 1947. From July 1945 to December 1947 Molybdenite Corporation of Canada, Ltd., milled 197,800 tons of ore, averaging 0.50 percent MoS_2. Operations were suspended on December 1, 1947, and resumed early in 1951 after a new and more efficient treatment process had been developed. The company negotiated a contract with the United States Government to supply 6 million pounds of molybdenite at over the prevailing market price in 1953. The mine has been Canada's only source of molybdenum in recent years. Other mines and areas in Canada from which molybdenum has been produced are as follows:

1. Clinton district
2. Dome mine
3. Martel mine
4. Molly mine
5. Moss mine
6. Nakina mine
7. North American—Regina, McCoy, and Zenith Cos.
8. Renfrew County

Canada had no facilities for converting molybdenite concentrate into primary products; consequently, its production was exported, mainly to the United States and Europe. However, a plant for converting concentrate to molybdic oxide was reported to have been constructed in 1956.

CHILE

Chile is second only to the United States in the production of molybdenum. Except for a few tons of molybdenite concentrate produced at Cupane near Tacona, in the northern part of Chile, during World War I, all output is from byproduct recovery of molybdenite contained in copper ores of the El Teniente mine of the Braden Copper Co. at Sewell.

The Braden Copper Co., a subsidiary of Kennecott Copper Corp., inaugurated recovery of molybdenite from its copper operations in 1939, when concentrate containing about 66,000 pounds of molybdenum was produced. Peak production of about 3.8 million pounds was made in 1951 as a result of the installation in 1950 of an improved selective flotation system that greatly increased the recovery of molybdenite. Byproduct production of molybdenum contained in concentrate from the Braden Copper operations for 1939–54 has amounted to almost 28 million pounds.

Since Chile has no facilities for converting molybdenite concentrate into primary products its production is exported, mostly to Europe.

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JAPAN

Japan has no important molybdenum deposits, and Japanese mines have satisfied only a small part of the demand of Japanese industry for molybdenum concentrate.

Molybdenum was first produced in Japan in 1908, and by the end of 1920 about 475,000 pounds had been produced from several mines.

No further output was made until 1934. During World War II the Japanese Government offered high subsidies and other concessions to producers of molybdenum, which stimulated production to a peak of over 400,000 pounds in 1944.

Four mines—the Hirase, Yamasa, Okowome, and Seikyu—supplied about 55 percent of the total output from 1934 to 1945 (*44*). Many other mines and prospects supplied the remaining 45 percent.

Molybdenum mining in Japan was suspended temporarily at the end of World War II but was resumed on a small scale in October 1945. The reserves of low-grade ore, which were blocked out during the highly subsidized wartime operations, were small and relatively unimportant.

The Honshu, Shimane, and Yamasa mines in Gifu Prefecture and the Taiyo-Daito mine in Shimane Prefecture are probably the only mines of any importance in Japan that were producing molybdenum in 1955.

Processing of molybdenum concentrate in Japan began on a small scale in the early 1920's, but the demand for concentrate did not exceed a few tons yearly until 1931, when Japan's first ferromolybdenum plant was built. The large ferromolybdenum capacity established created a demand for concentrate that greatly exceeded the output of domestic mines. The deficit was met by importing concentrate, first from Korea and later from the United States, South America, and Manchuria.

Japan's output of ferromolybdenum increased from 21 metric tons in 1931 to a peak of 1,802 metric tons in 1940. No production was reported in 1948; but it was resumed in 1949, reaching a postwar peak in 1954 of approximately 690 metric tons. During 1935–54 Japan's ferromolybdenum production totaled about 8,500 metric tons.

According to a report (*52*) on metallurgical plants of Japan prepared by General Headquarters Supreme Commander for the Allied Powers, the Tsukuda ferromolybdenum plant, at 18, 5-chome, Tsukuda-Cho, Nishi Yodogowaku, Osakashi, Osaka, has two electric furnaces with a designed capacity of 600 metric tons per heat.

Japan's production of metallic molybdenum powder and other molybdenum products increased gradually from 2 metric tons in 1931 to 123 in 1944. Suwa, Aoto, Sunamachi, Toko-Denki, Horikawacho, Niigate, Kobe, and Fushimi are the principal plants that produce molybdenum powder.

Salient statistics on molybdenum in Japan, 1925–55, are given in table 7.

TABLE 7.—*Salient statistics of molybdenum in Japan, 1925–55, in metric tons*

Year	Concentrate mine production [1]	Imports [2]	Ferromolybdenum production [3]	Refined molybdenum production [4]
1925		9		1
1926		7		1
1927		29		1
1928		31		1
1929		30		3
1930		26		1
1931		24	21	2
1932		45	85	3
1933		105	286	5
1934	3	103	132	5
1935	4	106	188	5
1936	4	80	199	6
1937	2	539	285	9
1938	1	1,025	672	15
1939	17	4,361	1,415	20
1940	14	1,271	1,802	26
1941	19	677	988	29
1942	39	1,500	546	38
1943	84	1,154	365	122
1944	188	1,858	337	123
1945	95	92	[5] 72	41
1946	52	N. a.	14	N. a.
1947	21	N. a.	2	40
1948	1	N. a.		27
1949		N. a.	209	16
1950	13	38	141	7
1951	54	75	93	15
1952	89	115	163	N. a.
1953	180	219	334	N. a.
1954	206	702	693	N. a.
1955	199	N. a.	N. a.	N. a.

[1] Contained molybdenum.
[2] Gross weight of concentrate.
[3] Gross weight (contains about 62 percent molybdenum).
[4] Mostly powder products, but includes wire and rods.
[5] Partial year.
N. a.—Not available.

Source: General Headquarters Supreme Commander for the Allied Powers, Tungsten and Molybdenum Metallurgy of Japan: Nat. Res. Sec., Rept. 61, 1946, and Japanese Ministry of International Trade and Industry, Mines Bureau.

MEXICO

A few tons of molybdenum concentrate was produced from small mining operations during World War I; but production was very small until 1933, when recovery of molybdenite concentrate as a byproduct of copper operations of Greene Cananea Copper Co., Cananea, Sonora, was inaugurated. For the next several years Mexico was the world's second largest producer of molybdenum, reaching maximum production in 1943, when concentrate containing over 2.5 million pounds of molybdenum was produced. However, in 1947 the Greene Cananea Copper Co. discontinued mining the deeper ores in which molybdenum is a constituent, and no further production was reported from Mexico until the Cía. Minera Bemnewilco, in the municipality of Nacozari Garcia, Sonora, began producing molybdenite concentrate in January 1954.

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There are a score or more of known molybdenum deposits scattered through the States of Baja California, Chihuahua, Coahuila, San Luis Potosi, Sinaloa, and Sonora that are not being worked, but little or no information is available on the size of deposits.

In recent years Mexico has imported small amounts of molybdenite concentrate from the United States.

NORWAY

The first known production of molybdenum was in Norway. The mineral molybdenite is reported to have been produced from the Knaben mine in the Knaben-Flekkefjord district, southern Norway, at the end of the 18th or the beginning of the 19th century. In 1880 work was resumed in the Knaben mine, and in the same year the Tjaerdolskampen deposit in Saltdalen, northern Norway, was discovered. Work at the latter was abandoned after a few years. Production was irregular and small for many years.

The first flotation plant in Norway was reported to have been installed at the Kvina mine in the Knaben-Flekkefjord district in 1913 (*9*). The Knaben mine was reopened the following year, and at the outbreak of World War I the two mines were producing molybdenite concentrate. During World War I and in later years several small molybdenite mines were worked in the Knaben area, at Oterstrand and Laksaadal in northern Norway, and at Sorumsaasen in the Drammen area near Oslo; but production was small, and working of the mines was discontinued.

Most of the molybdenite concentrate produced in Norway has been from the Knaben mine, which is controlled by Swedish interests. The ore is reported to be low grade, with only 0.15 to 0.20 percent MoS_2.

The Kvina mine, owned by the Derby Co. of London, was reopened in 1952 after having been closed for a long period. Production was small, and the mine was again closed in the summer of 1955.

YUGOSLAVIA

Molybdenum production in Yugoslavia has been small. Before World War II the only source of molybdenum was wulfenite recovered as a byproduct of lead-zinc mining at the Mezica mine. However, in 1943 Germany developed the Mackatica mine and erected a power station and flotation plant with a daily capacity of 500 metric tons. Although the ore was of such low grade that molybdenum concentrate produced was very costly, the mine and mill were operated until 1947 and produced about 500 metric tons of concentrate.

Molybdenum ores have also been found in Tande and Kopavnik in Serbia, but no information is available regarding production from these sources.

In 1948 Yugoslavia built a plant for manufacturing calcium molybdate, and no exports of molybdenum concentrate have been reported since.

Yugoslavia imported minor quantities of molybdenum concentrate in 1948, 1949, and 1952, all from Switzerland, Sweden, and the United Kingdom.

OTHER

Austria, China, Finland, France, French Morocco, Hong Kong, Indochina, Italy, Korea, Peru, Rumania, Spain, Sweden, and U. S. S. R. are among other countries known to have produced molybdenum, but, for the most part, production has been small and relatively unimportant. Little information is available regarding molybdenum production in the U. S. S. R. Shimkin (*61*) concludes that Soviet production has been small, but it is believed by other sources that important quantities of molybdenum are probably produced from the deposit east of Kounrad near Lake Balkhash.

Some mines in several countries from which molybdenum is known to have been produced are as follows:

Austria

1. Bleinberg-Kreuth
2. Dirstentritt
3. Scheinitzen

Bolivia

4. Illampu Mountain

Burma

5. Burma

El Salvador

6. San Salvador

French Cameroon

7. N'Kongsamba mine

Finland

8. Matasvarra

Greece

9. Axiapolis mine

Italy

10. Miess mine

Korea

11. Choswil

Morocco

12. Azegour mine

Manchuria

13. Yangchia-Changtze

Peru

14. Peru Molibdeno

Rumania

15. Margarets mine

Sweden

16. Udd mine (Orebrolan)
17. Algruen mine (Vasteras)

U. S. S. R.

18. Korabski mines
19. Tryny-Auz

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FIGURE 15.—Principal Commercial Forms and Uses of Molybdenum.

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FORMS, PROPERTIES, AND USES

COMMERCIAL FORMS AND USES

Figure 15 shows the principal commercial forms and uses of molybdenum from ore to end products. The iron and steel industry has been by far the most predominant user of molybdenum since about the beginning of the 20th century. It is estimated that, of all molybdenum consumed in 1955, the iron and steel industry used 85 to 90 percent, nonferrous alloys 4 to 6 percent, metal 3 to 4 percent, and nonmetallurgical 3 to 5 percent. Consumption of molybdenum as metal, in nonferrous alloys, and in nonmetallurgical applications is increasing, but owing to its steady growth as an alloying element in iron and steel the ratios of consumption may not be subject to radical change.

Molybdenum is used in many forms. Some of the more important commercial forms follow:

CONCENTRATE

All molybdenum minerals require concentration. Molybdenite (MoS_2) is the chief commercial molybdenum mineral. It is concentrated to about 54- to 95-percent molybdenum disulfide content before conversion to other products, but 90 percent is considered a standard grade for price quotations. United States Government purchase specifications for molybdenum concentrate are:

	Percent by weight
Molybdenum disulfide (MoS_2)	80.00 minimum.
Copper (Cu)	1.00 maximum.
Lead (Pb)	.30 maximum.
Phosphorus (P), Tin (Sn), Arsenic (As)	.20 maximum combined.

A purified molybdenite concentrate is also produced that contains over 99.9 percent MoS_2, for use in manufacturing molybdenum disulfide lubricants.

MOLYBDIC OXIDE

Molybdic oxide (MoO_3) is produced in several grades. The technical grade (roasted concentrate) is a raw material for producing all types of molybdenum salts and compounds and is also added to iron and steel, either with the charge or to the molten bath. This product contains most of the residual gangue material present in the mine concentrate. United States Government purchase specifications for technical-grade molybdic oxide are:

	Percent by weight
Molybdenum (Mo)	55.00 minimum.
Copper (Cu)	1.00 maximum.
Phosphorus (P)	.05 maximum.
Sulfur (S)	.25 maximum.

PURIFIED

Purified molybdic oxide is employed as a raw material for producing molybdenum, chemically pure molybdenum salts and compounds, and master alloys used in manufacturing high-temperature alloys. Its molybdic oxide content generally exceeds 99.5 percent.

BRIQUETS

Molybdic oxide briquets are a mixture of technical grade molybdic oxide and carbon that is added in the form of pitch. The product is used in the manufacture of iron and steel. Each briquet, containing exactly 2.5 pounds of molybdenum, has the following typical composition:

	Percent by weight
Molybdenum (Mo)	51.6
Carbon (C)	12.0 (approximate)
Copper (Cu)	.50
Sulfur (S)	.25
Phosphorus (P)	.05
Balance	Mainly SiO_2

METAL

Molybdenum powder of about 99-percent purity is produced by reducing purified molybdic oxide. The powder can be processed further by either of two methods, sintering or arc melting.

Technical thermite molybdenum is produced by Climax Molybdenum Co. in much the same way as it produces ferromolybdenum. It is used almost exclusively for addition to nonferrous alloys. Its typical composition is as follows:

	Percent by weight
Molybdenum (Mo)	95.0 minimum.
Carbon (C)	.05 maximum.
Sulphur (S)	.10 maximum.
Phosphorus (P)	.04 maximum.
Copper (Cu)	.50 maximum.
Silicon (Si)	1.50 maximum.
Iron (Fe)	2.50 maximum.
Balance	Principally slag.

FERROMOLYBDENUM

Ferromolybdenum produced from technical-grade molybdic oxide by the thermite process

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and by the electric furnace is added to iron and steel, either with the charge or to the molten bath. United States Government purchase specifications are:

	Percent by weight	
	Grade A	Grade B
Molybdenum (Mo)	55.00 minimum	55.00
Carbon (C)	2.50 maximum	.25
Copper (Cu)	1.00 maximum	1.00
Phosphorus (P)	.10 maximum	.10
Silicon (Si)	1.50 maximum	1.50
Sulfur (S)	.25 maximum	.25

OTHER

Ammonium molybdate, calcium molybdate, molybdenum silicide, and sodium molybdate are other commercial molybdenum products.

The uses of molybdenum as a metal, as an alloying element in iron, steel, and special and nonferrous alloys and in nonmetallurgical applications are described individually in this section.

MOLYBDENUM

Molybdenum, with atomic number 42, is a member of group V of the periodic table. It does not occur free in nature. The pure metal is silvery white and softer than steel. It melts at 2,622±40° C., compared with about 1,375° C. for steel. Only four other elements (carbon, rhenium, tungsten, and tantalum) have higher melting points. Chemically it exhibits valences in stable compounds of 2, 3, 4, 5, and 6. Its oxides and salts combine with organic hydroxyl and carbonyl compounds. Molybdenum has good thermal conductivity—about half that of copper. Its coefficient of thermal expansion is among the lowest of pure metals. The physical properties of molybdenum are listed in table 8.

In recent years considerable research has been devoted to molybdenum in an effort to produce a higher purity metal, to overcome its inability to withstand oxidation in air at high temperatures, and to improve fabrication. The production of high-purity molybdenum by electrodeposition has revealed many conflicting results by different investigators; but, with the exception of the work reported by Brenner and Senderoff (*74*), it is doubtful that satisfactory deposits have been obtained.

Several methods of protecting molybdenum from rapid oxidation in air at high temperatures have been investigated. Ceramic coatings, cladding, electroplating, metal-dip coatings, metal-spray coatings, and vapor-phase depositions are among the methods of surface protection that have been investigated in recent years; however, all have certain shortcomings and are not being used commercially.

TABLE 8.—*Physical properties of molybdenum* [1]

Atomic number	42.	
Atomic weight	95.95	
Crystal structure	Body-centered cubic.	
Valence	2, 3, 4, 5, 6.	
Melting point	2,622°±40° C.	
Boiling point	4,804° C.	
Vapor pressure	*Atmosphere*	*Temperature,° C.*
	0.0001	2,727
	.001	3,057
	.01	3,477
	.1	4,027
	.25	4,307
	.5	4,537
	1.0	4,804
Specific heat	0.058 cal. per gm. per ° C. at 25° C.	
Thermal conductivity	*Cal.-cm.-sec.-° C.*	*Temperature,° C.*
	0.346	17
	.259	927
	.159	1,627
Electrical resistivity	*Microhm-cm.*	*Temperature,°C.*
	5.2	0
	5.78	27
	23.9	727
	29.2	927
	35.2	1,127
	41.2	1,327
	47.2	1,527
	53.5	1,727
	59.5	1,927
	66.0	2,127
	69.2	2,227
	71.8	2,327
	78.2	2,527
	81.4	2,622
Coefficient of linear expansion.	5.35×10^{-6} per °C.—0° to 20° C.	
	5.7×10^{-6} per °C.—0° to 500° C.	
Density calculated [2]	10.23 gm. per cc.	
Powder	10.28	
Cast 2-in. section	10.2	
Sintered 1-in. section	9.6	
Sintered, swaged, drawn	10.2	
Avogadro number	6.0228×10^{23}	
Young's modulus of elasticity.	47.7×10^{6} p. s. i.	
	49.4×10^{6} p. s. i.	
Lowest temperature of recrystallization.	870°±25° C.	

[1] Archer, R. S., Briggs, J. Z., and Loeb, Jr., C. M., Molybdenum—Steels, Iron, Alloys: Climax Molybdenum Co., 1948, pp. 362-363.
[2] Using kx=3.1399.

PRODUCTION AND USES

Molybdenum, produced by both powder metallurgy and by arc melting, can be swaged, forged, rolled, drawn, and formed. According to Parke (*56*), metal produced by powder metallurgy has a very fine and equiaxed grain structure that can be readily worked, while arc-melted molybdenum has a coarse, columnar grain structure that requires an initial, high-temperature, hot forging or rolling operation to break down the grain structure before

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working by the same methods employed for the powder-metallurgy product. According to Climax Molybdenum Co. (*72*), the following five general characteristics of metallic arc-cast molybdenum and its alloys should be kept in mind in all working operations:

1. The mechanical properties of unalloyed molybdenum and the four alloys commercial today depend to a large degree on the amount of working done below the recrystallization temperature (so-called warm working). For optimum ductility, parts should be given at least a 50-percent reduction in area by warm working.
2. Full recrystallization gives lower strengths than do other prior treatments, so fully recrystallized molybdenum flows more easily in working. It does, however, have very poor bending properties although the tensile elongation is higher than in other conditions. Therefore, fully recrystallized molybdenum is used for the fabrication of parts only if no bending or deep drawing is to be done; or if mechanical properties after working are not important; or if subsequent processing will involve sufficient warm work to produce the necessary properties.
3. Relative to its high melting and recrystallization temperatures, molybdenum is much "colder" at room temperature than steel. The toughness and ductility of molybdenum are consequently not very high at room temperature although they increase markedly at temperatures somewhat above room temperature (for example 400° F.). Therefore, except for fine wire and sheet, at least a moderate amount of heating is recommended for all working operations.
4. Because of its high thermal conductivity and low specific heat, molybdenum heats and cools much more rapidly than steel.
5. Molybdenum and its alloys have unusually high strength at elevated temperatures. Therefore, for a given amount of work, more powerful presses and hammers are needed than for any of the other common metals.

The welding and brazing of molybdenum present problems that are not easily overcome, because air and other sources of oxygen must be excluded from the weld. The high melting point and thermal conductivity of molybdenum must also be considered. Thermal conductivity of molybdenum causes problems somewhat similar to those encountered when copper and aluminum are welded. The weld bead and adjacent heat-affected parent metal have properties typical of recrystallized metal that makes it brittle and unsuitable for some applications. For these reasons, welding of complicated sheet-metal structures presents fabrication problems. Riveting and lock seams are by far the simplest and most flexible methods of joining molybdenum, but gastight joints cannot be made by these methods.

Although encouraging results have been obtained in overcoming oxidation in air at temperatures above 1,000° F. and in solving problems of welding the pure metal, its uses are still rather limited, being confined mostly to lead wires for incandescent lamps, heating elements in electric furnaces, grid wires and high-temperature parts in electronic tubes, electrodes for melting glass, furnace boats, radiation shields, heavy-duty contact breakers, and seamless tubing for the chemical industry. The behavior of molybdenum with various reagents is given in table 9.

MOLYBDENUM IN STEEL

HISTORY

Molybdenum as an alloying element was doubtless first used in steel. It is said (*15*) that a German steel expert analyzed part of a sword blade made by the famous Japanese artist Masamune (1330) and found that it contained molybdenum. Probably the earliest intentional use of molybdenum in steel was in 1894, when Schnieder & Co. produced armorplate containing molybdenum at its Creusot works in France. However, the use of molybdenum in steel remained experimental until about 1898, when the Sanderson Steel Co. marketed a self-hardening, molybdenum tool steel. In the following years molybdenum, as an alloying element in tool steels, attracted widespread interest, but metallurgists found that, upon heat treating, molybdenum high-speed steels were susceptible to surface decarburization, and tools made from the steels gave erratic performance, owing largely to lack of knowledge of the critical heat-treating range and adequate heat-treating equipment. The proper heat-treating range and protection against decarburization were developed and demonstrated at Watertown Arsenal in 1930.

Early experimentation with molybdenum tool steels determined that the effect of molybdenum was in the same direction but of greater magnitude than that of tungsten; but, probably because of limited supply and lack of economic advantage, little further interest was shown in molybdenum as an alloying element until World War I (1914–18), when the European Governments found it necessary to substitute molybdenum in part for tungsten in high-speed steels. During that war period molybdenum was also used to some extent as an alloying element in manufacturing relatively low alloy steels that were used in certain military equipment. However, after the close of World War I the demand for molybdenum as an alloying element in steel decreased. This, plus large stocks at mines and industrial plants, was largely responsible for the collapse of the molybdenum-mining industry.

Probably the first peacetime application of molybdenum-bearing, low-alloy steels was in the summer of 1920, when it is said that molybdenum steels were used in Studebaker automobiles (*33*). By 1925 the automotive industry was aware of the value of molybdenum as an alloying element in low-alloy steels, and the Society of Automotive Engineers adopted the 4100 (chromium-molybdenum) series steels. This not only marked the beginning of a new

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TABLE 9.—*Behavior of metallic molybdenum with various reagents* [1]

Reagent	Temperature, °C.	Concentration	Form of Mo	Action of Mo
Water	Room		Powder	Oxidized.
	do		Solid	Surface oxidation.
	Red heat		Either	$Mo+2H_2O \rightleftharpoons MoO_2+2H_2$.
Air or oxygen	20°		Solid	Surface oxidation.
	Above 500°		do	Rapid oxidation.
Hydrogen				No action.
Nitrogen	Up to 1,500°			Slight absorption.
Ammonia (anhyd.)	850°		Powder	Action forms brown powder.
Ammonia solution	Room		Foil	Blackens, dissolves.
Hydrogen sulfide	1,200°		Powder	Reacts to form sulfide.
Carbon dioxide or monoxide.	Above 1,200°		do	Oxidized.
Oxides of nitrogen	Red heat		do	Do.
Sulfur dioxide	do		do	Do.
Aqua regia	Warm		Metal	Rapid reaction, slow in the cold.
Hydrochloric acid	Hot	Dil	do	Rapid reaction.
	Cold	Concd	do	Resists action.
Hydrofluoric acid	Cold or warm	Soln	do	Do.
$HF+HNO_3$			do	Dissolves.
Sulfuric acid	Room	Concd	do	Slow action.
	200–250	do	do	Rapid reaction.
	To 110	Dil	do	Resists action.
Nitric acid	Room	Concd	do	Slowly forms protective layer of MoO_3.
	do	Dil	do	Rapid solution
Potassium hydroxide	do	Soln	do	No reaction reported.
Sodium hydroxide	Hot	do	do	Weak reaction.
	do	Fused	do	Solution with evolution of H_2, forms molybdate.
Oxidizing salts (KNO_2, KNO_3, Na_2O_2, $KClO_3$).	do	do	do	Violent reaction.
$AlCl_3$—NaCl	150–370	do	do	No action.
Carbon and hydrocarbons	High temps		Metal or powder	Forms carbides.
Mercury			do	No perceptible action (Hg dissolves only 2×10^{-6} percent Mo).
Phosphorus			do	No reaction reported.
Silicon	2,000		do	Forms silicides.
Sulfur	Above 440		do	Forms sulfides.
Fluorine	Room		do	Forms fluorides.
Chlorine	do		do	Forms chlorides.
Bromine	Bright red		do	Forms bromides.
Iodine	To 500		do	No reaction reported.
Boron	Electric furnace		do	Forms borides.
Leaded nitrate		Solns	do	No reaction reported.
Bismuth and cadmium salts.		do	do	Do.
Copper salts		do	Metal	Cu precipitated.
Ferric chloride		do	do	Reacts.
Lead dioxide	Heated		Powder	Forms lead molybdate.

[1] Killeffer, D. H., and Linz, Arthur, Molybdenum Compounds—Their Chemistry and Technology: Interscience Publishers, 1952, pp. 18–19.

and perhaps a greater molybdenum industry than had been imagined, but wide use of molybdenum-bearing low-alloy steels by the automotive and other industries made it necessary for the molybdenum producers to increase production severalfold before World War II.

Although molybdenum high-speed steels were first accepted for peacetime use in 1931, they were only used to a limited extent before World War II. The shortage of tungsten created by developments of the war made it necessary to substitute molybdenum in part for tungsten in high-speed and some other alloy tool steels. Because of an ample supply of molybdenum, suitable heat-treatment practices, and a favorable price structure molybdenum tool steels are now widely accepted for peacetime uses.

As a result of the enormous increase in production of alloy steels and a shortage of alloying elements during World War II, the War Production Board organized a committee to devise some new steels that would make the most effective use of the available alloying elements. The committee proposed the so-called National Emergency steels (nickel, chromium, and molybdenum), which greatly increased the use

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of molybdenum. Several series of the National Emergency steels were later adopted by the American Iron and Steel Institute and are now standard.

The range in composition of molybdenum steels can roughly be divided into high-molybdenum steels that contain over 0.5 percent of molybdenum and low-molybdenum steels that contain 0.10 to 0.5 percent of molybdenum.

Table 10 gives the molybdenum consumed in the manufacture of alloy steel in the United States for 1946–55.

TABLE 10.—*Molybdenum consumed in manufacturing alloy steel in the United States, 1946–55* [1]

[American Iron and Steel Institute]

Year:	*Molybdenum, in thousand pounds*
1946	10,767
1947	13,447
1948	16,349
1949	11,244
1950	17,243
1951	18,562
1952	16,233
1953	18,696
1954	14,179
1955	21,318

[1] Does not include molybdenum contained in scrap.

FORMS ADDED TO STEEL

In steelmaking, molybdenum is used in the form of molybdic oxide, ferromolybdenum, calcium molybdate, and, to a limited extent, molybdenum disulfide.

The form of molybdenum used in alloying cast and wrought steels depends largely on the steelmaking process, economics, and the type of steel being produced. Ferromolybdenum is adaptable to any of the processes, but the relatively lower cost per unit of molybdenum is responsible for use of the other forms.

For many years in the United States calcium molybdate and ferromolybdenum were used more widely than molybdic oxide, but recently the tendency has been to use more molybdic oxide than either calcium molybdate or ferromolybdenum. Some European countries still use ferromolybdenum more extensively than the oxide. A relatively small quantity of molybdenite (MoS_2) is used by some steel producers as an addition to molten steel in the ladle when the addition of both sulfur and molybdenum is desired.

In general, when an entire open-hearth or electric furnace heat is to be alloyed to a degree not exceeding 1.0 percent of molybdenum, the addition is in the form of molybdic oxide or calcium molybdate; but, when higher percentages of molybdenum are desired, ferromolybdenum is used for that part of the addition exceeding about 1.0 percent.

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ALLOYING EFFECT

The alloying effects of molybdenum in steel are derived both from its effect in solid solution in ferrite and from its effect in the carbide phase. Molybdenum in solid solution in ferrite contributes to increased strength of steel, and many molybdenum-bearing steels are used in the as-rolled condition because of this factor. The creep resistance and strength of both low- and high-alloy steels at elevated temperatures are increased by the solid solution of molybdenum in ferrite. The major contributions of molybdenum to steel are derived from its effect on microstructure during heat treating.

HARDENABILITY

Although the carbon content of a steel determines the maximum hardness that can be imparted by quenching from above its critical temperature range, molybdenum dissolved in austenite retards the rate of transformation to pearlite and ferrite, thereby reducing the critical cooling rate of the steel. This reduced critical cooling rate allows use of slower cooling mediums, which causes the steel to harden more evenly from surface to center. However, since molybdenum is predominantly present in the carbide phase of annealed steel and dissolves more slowly and at higher temperatures than iron carbide, the heating must be such as to assure solution in austenite before quenching. This uniform hardening (sometimes called depth hardening) is of particular benefit in heat-treating heavy sections of steel, because internal stress that may lead to cracking or distortion is greatly reduced. Many construction alloy steels used in the hardened or hardened and tempered condition contain about 0.10 to 0.50 percent molybdenum for its contribution to hardenability. Larger amounts of molybdenum promote secondary hardening and are used in some steels where this effect is desired. High-speed tool steels contain up to about 9 percent molybdenum, for its effect on hardness and strength at the high temperatures developed during cutting operations. Although the critical temperature range of these steels is considerably higher than for the lower alloy steels, the function of molybdenum is generally the same, except for precipitation of larger amounts of molybdenum-bearing carbides during cooling, which imparts greater hardness (red hardness) to the steels.

PROPERTIES AT ELEVATED TEMPERATURES

Molybdenum is one of the most effective alloying elements for increasing the strength and creep resistance of both low- and high-alloy steels at elevated temperatures. The exact function of molybdenum in imparting these properties to steel is not fully known, although

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research has determined that high-purity iron-molybdenum alloys show a marked increase in the creep strength of ferrite and the lowest temperature of recrystallization after strain hardening. Molybdenum in quantities up to about 0.5 percent is used extensively to combat embrittlement in certain steels that are either tempered in the temperature range from about 850° to 1,100° F. or subjected to stresses and strains during service at these elevated temperatures. Although little is known of the cause of steels becoming brittle in this temperature range or of the effect of molybdenum in retarding the condition, it has been determined that steels of higher hardenability are generally more susceptible. For that reason, molybdenum is extensively used in highly hardened steels, such as armorplate, for its effect on (temper) brittleness, as well as on hardenability.

RESISTANCE TO CORROSION

Molybdenum materially aids certain grades of stainless steel in resistance to surface corrosion and probably intergranular corrosion. About 2 to 3 percent of molybdenum in chromium-nickel (18 percent chromium, 8 percent nickel) stainless steels helps to prevent corrosion caused by corrosive deposits settling on the steel, and it is reported (*47*) that, when the microstructure of austenite chromium-nickel steels is such that some delta ferrite is present, it retards intergranular corrosion.

OTHER PROPERTIES

Even though molybdenum is a strong carbide-forming element, it does not cause excessive concentration of carbon on the surface of carburizing steels during carburization and is widely used in those steels for its effect in improving such properties as strength and impact resistance.

The tendency of molybdenum to promote free scaling of steels heated in an oxidizing atmosphere is beneficial in forging, and in die steels where a tightly adhered scale would lead to surface defects in the forging or excessive wear of the dies.

HIGH-STRENGTH ENGINEERING AND STRUCTURAL ALLOY STEELS

The groups of alloy steels often referred to as high-strength engineering and structural steels are largely used in the hardened or hardened and tempered condition for the improved mechanical properties imparted by heat treating. These steels generally contain a combination of alloying elements, because smaller quantities of the elements in combination give mechanical properties equal or superior to those when a larger quantity of a single alloying element is used. The desired improved mechanical properties include: Greater tensile strength, resistance to wear, strength at elevated temperatures, resistance to impact, and resistance to fatigue. Although all of these steels do not contain molybdenum, it is added to a larger proportion of them in quantities ranging from as little as 0.08 percent in some of the lower alloy steels to about 1.0 percent in some special-purpose high-alloy steels. The chemical and physical specifications of these steels are voluminous, and therefore only the chemical specifications of the types containing molybdenums that have been adopted by the American Iron and Steel Institute are given in table 11. Those steels fall into the following general groups: Carbon-molybdenum, nickel-molybdenum, nickel-chromium-molybdenum, chromium-molybdenum, and manganese-molybdenum. The United States production of these steels, by group classifications, is

TABLE 11.—*Open-hearth and electric-furnace molybdenum-bearing alloy steels*

[American Iron and Steel Institute]

AISI No.	Chemical composition ranges and limits, percent							
	Carbon	Manganese	Phosphorus, maximum	Sulfur, maximum	Silicon	Nickel	Chromium	Molybdenum
4023	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35			0.20–0.30
4024	.20–.25	.70–.90	.040	.035–0.050	.20–.35			.20–.30
4027	.25–.30	.70–.90	.040	.040	.20–.35			.20–.30
4028	.25–.30	.70–.90	.040	.035–.050	.20–.35			.20–.30
4032	.30–.35	.70–.90	.040	.040	.20–.35			.20–.30
4037	.35–.40	.70–.90	.040	.040	.20–.35			.20–.30
4042	.40–.45	.70–.90	.040	.040	.20–.35			.20–.30
4047	.45–.50	.70–.90	.040	.040	.20–.35			.20–.30
4053	.50–.56	.75–1.00	.040	.040	.20–.35			.20–.30
4063	.60–.67	.75–1.00	.040	.040	.20–.35			.20–.30
4068	.63–.70	.75–1.00	.040	.040	.20–.35			.20–.30

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TABLE 11.—*Open-hearth and electric-furnace molybdenum-bearing alloy steels*—Continued

[American Iron and Steel Institute]

AISI No.	Chemical composition ranges and limits, percent							
	Carbon	Manganese	Phosphorus, maximum	Sulfur, maximum	Silicon	Nickel	Chromium	Molybdenum
4118	0. 18–0. 23	0. 70–0. 90	0. 040	0. 040	0. 20–0. 35	----------	0. 40–0. 60	0. 08–0. 15
4130	. 28– . 33	. 40– . 60	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4135	. 33– . 38	. 70– . 90	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4137	. 35– . 40	. 70– . 90	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4140	. 38– . 43	. 75–1. 00	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4142	. 40– . 45	. 75–1. 00	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4145	. 43– . 48	. 75–1. 00	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4147	. 45– . 50	. 75–1. 00	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4150	. 48– . 53	. 75–1. 00	. 040	. 040	. 20– . 35	----------	. 80–1. 10	. 15– . 25
4320	. 17– . 22	. 45– . 65	. 040	. 040	. 20– . 35	1. 65–2. 00	. 40– . 60	. 20– . 30
4337	. 35– . 40	. 60– . 80	. 040	. 040	. 20– . 35	1. 65–2. 00	. 70– . 90	. 20– . 30
E4337	. 35– . 40	. 65– . 85	. 025	. 025	. 20– . 35	1. 65–2. 00	. 70– . 90	. 20– . 30
4340	. 38– . 43	. 60– . 80	. 040	. 040	. 20– . 35	1. 65–2. 00	. 70– . 90	. 20– . 30
E4340	. 38– . 43	. 65– . 85	. 025	. 025	. 20– . 35	1. 65–2. 00	. 70– . 90	. 20– . 30
4608	. 06– . 11	. 25– . 45	. 040	. 040	. 25 max.	1. 40–1. 75	----------	. 15– . 25
4615	. 13– . 18	. 45– . 65	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
4617	. 15– . 20	. 45– . 65	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
4620	. 17– . 22	. 45– . 65	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
X4620	. 18– . 23	. 50– . 70	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
4621	. 18– . 23	. 70– . 90	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
4640	. 38– . 43	. 60– . 80	. 040	. 040	. 20– . 35	1. 65–2. 00	----------	. 20– . 30
4720	. 17–0. 22	. 50– . 70	. 040	. 040	. 20– . 35	0. 90–1. 20	. 35–0. 55	. 15– . 25
4812	. 10– . 15	. 40– . 60	. 040	. 040	. 20– . 35	3. 25–3. 75	----------	. 20– . 30
4815	. 13– . 18	. 40– . 60	. 040	. 040	. 20– . 35	3. 25–3. 75	----------	. 20– . 30
4817	. 15– . 20	. 40– . 60	. 040	. 040	. 20– . 35	3. 25–3. 75	----------	. 20– . 30
4820	. 18– . 23	. 50– . 70	. 040	. 040	. 20– . 35	3. 25–3. 75	----------	. 20– . 30
8615	. 13– . 18	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8617	. 15– . 20	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8620	. 18– . 23	. 70– . 90	. 040	. 040	. 20– . 25	. 40– . 70	. 40– . 60	. 15– . 25
8622	. 20– . 25	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8625	. 23– . 28	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8627	. 25– . 30	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8630	. 28– . 33	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 70	. 15– . 25
8635	. 33– . 38	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8637	. 35– . 40	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8640	. 38– . 43	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8641	. 38– . 43	. 75–1. 00	. 040	. 040–0. 060	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8642	. 40– . 45	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8645	. 43– . 48	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8650	. 48– . 53	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8653	. 50– . 56	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8655	. 50– . 60	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8660	. 55– . 65	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 15– . 25
8715	. 13– . 18	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8717	. 15– . 20	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8720	. 18– . 23	. 70– . 90	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8735	. 33– . 38	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8740	. 38– . 43	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8742	. 40– . 45	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
8750	. 48– . 53	. 75–1. 00	. 040	. 040	. 20– . 35	. 40– . 70	. 40– . 60	. 20– . 30
E9310	. 08– . 13	. 45– . 65	. 025	. 025	. 20– . 35	3. 00–3. 50	1. 00–1. 40	. 08– . 15
E9314	. 11– . 17	. 40– . 70	. 025	. 025	. 20– . 35	3. 00–3. 50	1. 00–1. 40	. 08– . 15
9840	. 38– . 43	. 70– . 90	. 040	. 040	. 20– . 35	. 85–1. 15	. 70– . 90	. 20– . 30
9845	. 43– . 48	. 70– . 90	. 040	. 040	. 20– . 35	. 85–1. 15	. 70– . 90	. 20– . 30
9850	. 48– . 53	. 70– . 90	. 040	. 040	. 20– . 35	. 85–1. 15	. 70– . 90	. 20– . 30

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given in table 12, and their production compared with total alloy-steel production is given in table 13. Since it is impractical to fully discuss these steels in a report of this nature, only a brief reference is made to each general class.

TABLE 12.—*United States production of alloy steel (other than stainless) containing molybdenum, 1943–55, in short tons*

[American Iron and Steel Institute]

Year	Mo	Ni-Mo	Ni-Cr-Mo	Cr-Mo	Mn-Mo
1943	1,133,179	709,734	3,736,998	2,207,168	N. a.
1944	403,202	433,262	3,628,342	1,117,780	N. a.
1945	400,027	426,594	3,062,461	343,147	N. a.
1946	426,521	461,689	680,804	384,571	N. a.
1947	592,462	N. a.	878,353	347,867	N. a.
1948	653,823	N. a.	1,164,200	489,931	N. a.
1949	475,691	309,971	797,941	313,195	204,653
1950	636,012	469,525	1,289,771	544,280	251,819
1951	436,787	155,036	2,206,461	890,313	294,563
1952	366,077	159,177	1,704,570	1,191,840	195,444
1953	502,239	195,371	1,618,094	1,179,003	291,020
1954	505,408	365,240	865,355	668,314	307,215
1955	709,263	512,054	1,395,837	1,023,607	329,913

N. a.—Not available.

TABLE 13.—*Production of molybdenum-bearing alloy steel compared with total production of alloy steel (other than stainless) in the United States, 1943–55, in short tons*

[American Iron and Steel Institute]

Year	Total alloy steel (other than stainless)	Alloy steel containing molybdenum (other than stainless)	Total alloy steel (other than stainless) containing molybdenum, percent
1943	12,573,509	7,787,079	62
1944	10,050,013	5,582,586	56
1945	8,008,213	4,232,229	53
1946	5,432,656	1,953,585	36
1947	6,798,778	1,818,682	27
1948	7,760,820	2,307,954	30
1949	5,342,271	2,101,451	39
1950	7,613,740	3,191,407	42
1951	9,061,455	3,983,160	44
1952	8,086,681	3,617,108	45
1953	9,208,237	3,785,727	41
1954	6,225,636	2,711,532	44
1955	9,266,523	3,970,674	43

CARBON-MOLYBDENUM

Molybdenum in amounts of 0.2 to 0.3 percent is added to these steels to improve such physical properties as hardenability and strength. The steels are adaptable to production heat-treatment methods where the heat-treating temperatures each part receives may not be uniform. The low-carbon steels of this group are used both in the carburized and in the hardened condition. They have excellent weldability and may be welded more readily than a plain carbon steel developing the same tensile strength. The medium-carbon steels of this group are generally used for structural purposes where a fine grain structure is not required. Some grades are available slightly resulfurized to aid machinability.

The automotive, construction, machinery, mining, petroleum, power, and railway industries are large users of these steels.

NICKEL-MOLYBDENUM

The nickel-molybdenum steels are used chiefly for carburizing where superior case hardness or core properties are desired. The low-nickel-molybdenum steels (4600 series) are extensively used for such applications as gears, piston pins, and similar parts of moderate sections for relatively light service, and the higher nickel-molybdenum steels (4800 series) are used for heavy sections or severe service applications, such as aircraft-engine parts or machinery parts for heavy-duty service.

NICKEL-CHROMIUM-MOLYBDENUM

Nickel-chromium-molybdenum steels are used for heavy sections or for parts subject to particularly severe service conditions or for which very mild quenches must be used to prevent distortion. These steels are subject to air hardening and therefore must be prepared for machining by a suitable annealing cycle.

In heavy sections these steels develop a good combination of ductility and tensile strength. They resist softening at service temperatures. Some typical uses for these steels are hot-work dies, locomotive connecting rods, traction gears, drive shafts, airplane-propeller shafts, and hot shear blades.

CHROMIUM-MOLYBDENUM

The chromium-molybdenum steels were the first molybdenum-bearing engineering and structural alloy steels developed for commercial applications and are now among the most popular alloy steels, for they are relatively cheap and versatile, being especially well adapted to the fabrication procedures of forging, machining, and welding. Their properties make them particularly suitable for service characterized by fatigue, abrasion, impact, and high temperature stresses.

These steels free themselves of scale more readily than most alloy steels, with the result that forging, rolling, and pickling operations are conducted with minimum difficulty.

In the fully heat-treated state, chromium-molybdenum steels are easily machinable and compare favorably in this respect with plain carbon steels at the same hardness.

Chromium-molybdenum steels are easily welded, and it is often unnecessary to heat-treat the welds; but, if high strength is desired, a chromium-molybdenum welding rod of the same analysis should be used for welding and the weld heat-treated.

The automotive industry is probably the largest consumer of chromium-molybdenum steels,

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but the aircraft, oil, machine-tool, railway, and other industries are also large consumers.

MANGANESE-MOLYBDENUM

The manganese-molybdenum steels are used largely for castings. Molybdenum improves the uniform hardening of the steels, which greatly helps to prevent stresses and strains that probably would cause cracking of the thinner sections of the casting. The tonnage of these steels produced in the United States is small as compared with other groups of molybdenum-bearing steels.

HIGH-SPEED AND OTHER TOOL STEELS

Being a strong carbide-forming element, molybdenum makes its major contribution to high-speed steel through the formation of the face-centered cubic double carbide $(Fe, Mo)_6C$. Since its atomic weight (95.95) is about half that of tungsten (184.0), the quantity of molybdenum added to high-speed steel to obtain about the same degree of hardness is about half that of tungsten.

During normal cutting operations a high-speed tool becomes heated to about 1,100° to 1,250° F. at the point of contact (*27*). Therefore, the hardness of a high-speed steel at this elevated temperature range is more important than its room-temperature hardness. To develop proper hardness (red hardness) at this elevated temperature range it is necessary to exercise special care in heat treating the steel. Although the critical temperature range of molybdenum-type high-speed steels is lower than that for the tungsten type both must be held above their critical temperatures long enough to assure solution of a substantial percentage of the alloy carbides before quenching. Molybdenum-type high-speed steels are tempered in the range of about 1,000° to 1,150° F. to precipitate alloy carbides, reducing the alloy content in the retained austenite and resulting in secondary hardening.

During the past several years use of molybdenum-type high-speed steels in the United States has exceeded use of the tungsten type and in 1955 comprised over 86 percent of all high-speed steels shipped. Factors that prompted increased use of molybdenum-type high-speed steels included the following: A shortage of tungsten during the Korean War (1950–53) caused producers to use molybdenum as a replacement for tungsten; the cost of molybdenum was considerably less than that of tungsten; improved heat-treating equipment gave closer control during hardening and tempering; and for some applications molybdenum high-speed steels were preferred over tungsten type. United States production (as measured by shipments) of high-speed and other tool steels by major types is given in table 14. It is impractical to attempt to list the specific uses

TABLE 14.—*United States shipments of high-speed and tool steel, 1944–55, by major types, in short tons (exclusive of hollow drill steel)*

[American Iron and Steel Institute]

Grade [1]	Composition (percent) C (min)	Cr (max)	W (max)	Mo (max)	V	CO	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955
Class A—High-speed:																		
I	0.60	4.5	6.75	5.50	[2]2.10	0	6,656	6,490	4,798	4,008	5,622	2,540	6,161	19,398	11,821	11,311	6,446	10,504
Ib	.90	4.5	6.75	6.50	[2]2.25	0	126	569	37	51	85	104	154	557	549	566	489	847
Ic	.60	4.5	6.75	5.50	[2]2.20	[3]3.5	217	211	242	135	316	208	572	239	243	85	59	118
II	.60	4.5	2.00	9.25	[2]1.30	0	1,708	1,577	1,721	1,009	1,499	560	1,559	7,504	4,185	5,283	3,222	5,899
IIc	.60	4.5	2.00	9.25	[2]2.20	[3]3.5	119	67	30	26	35	26	42	270	214	176	139	153
III	.60	4.5	0	9.25	[2]2.20	0	1,083	1,050	400	289	665	151	948	2,421	2,811	3,684	2,443	4,088
IIIc	.60	4.5	0	9.25	[2]2.20	[3]3.5	235	79	26	45	83	29	73	178	25	44	17	7
Total, class A							10,144	10,043	7,254	5,563	8,305	3,618	9,509	30,567	19,848	21,149	12,815	21,616
Class B—High speed:																		
IV	.55	4.5	19.0	0	[2]1.30	0	16,881	13,634	8,574	9,804	7,949	4,041	6,823	6,061	1,601	2,336	1,838	2,366
IVb	.55	4.5	19.0	1.25	[2]1.75	0	423	455	307	500	436	391	546	499	204	259	204	284
IVc	.55	4.5	22.0	1.25	[2]2.20	[3]3.5	1,478	938	778	1,054	1,071	884	1,026	929	812	841	498	695
Total, class B							18,782	15,027	9,659	11,358	9,456	5,316	8,395	7,489	2,617	3,436	2,540	3,345
Total high-speed tool steels							28,926	25,070	16,913	16,921	17,761	8,934	17,904	38,056	22,465	24,585	15,355	24,961
Ratio of class A to total high-speed—percent							35.0	40.0	42.9	32.9	46.7	40.5	53.1	80.3	88.3	86.1	83.5	86.6
Other:																		
V. All hot-work steel							11,281	12,874	5,942	6,088	7,127	5,140	8,068	12,995	12,719	14,229	8,857	12,062
VI. High-Cr (4 percent min.) die steel							5,571	5,321	5,444	5,897	6,707	4,707	7,168	12,230	9,700	8,619	7,832	10,488
VII. All other alloy tool steels							38,820	44,234	40,043	36,605	37,988	26,251	40,891	78,621	57,103	53,257	40,342	52,949
VIII. Carbon tool steels							29,530	29,356	28,049	23,438	20,251	12,968	19,038	34,112	20,233	16,941	12,626	15,468
Total, other							85,202	91,785	79,478	72,028	72,073	49,066	75,705	137,958	99,755	93,046	69,657	90,967
Total all tool steels							114,128	116,855	96,391	88,949	89,834	58,000	93,609	176,014	122,220	117,631	85,012	115,928
Ratio of high-speed to total tool steels—percent							25.3	21.4	17.5	19.0	19.8	15.4	19.1	21.6	18.4	20.9	18.1	21.5
Ratio of class A high-speed to total tool steels—percent							8.9	8.6	7.5	6.3	9.2	6.2	10.2	17.4	16.2	18.0	15.1	18.6

[1] Before July 1, 1951, specifications for II, IIc, III, and IIIc called for 1.8 percent W and 8.75 percent Mo. [2] Maximum. [3] Minimum.

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of molybdenum-type, high-speed steels for they are not only interchangeable to a very large degree with tungsten-type high-speed steels, but shop practice is also an important factor in determining their use.

Molybdenum is also used quite extensively in other tool steels that can roughly be grouped into four main types: (1) Hot-work; (2) cold-work; (3) shock-resisting; and (4) special-purpose. Molybdenum is added to these steels for its contribution to hardness, toughness, wear resistance, or some other desired property. Its function in hot-work steels is the same as in high-speed steels.

In nondeforming die steels molybdenum increases hardenability and minimizes distortion during heat treatment. The molybdenum content in these steels varies from about 0.25 to 1 percent.

Molybdenum in shock-resisting steels contributes to greater resistance to shock. It is normally added to these steels in 0.15- to about 0.5-percent amounts.

Molybdenum in amounts of 0.15 to about 2 percent is used in many special-purpose and miscellaneous tool steels that have a wide variety of applications.

MOLYBDENUM IN CAST IRON

HISTORY

Addition of molybdenum to cast iron was primarily experimental until the late 1920's. In 1929 Cone (*11*) conducted a survey of iron foundries in the United States and reported that molybdenum was being used in manufacturing rolls for rolling mills and also in certain types of castings for automobiles and airplanes but that the latter was only recent.

In early use cast iron produced by or for automotive companies contained 0.30 to 1.00 percent of molybdenum, which was generally used alone, but it was soon determined that molybdenum, in combination with other alloying elements, such as chromium and nickel, resulted in more desirable castings.

During the 1930's the use of molybdenum in cast iron spread to virtually every industry that needed high-strength castings. Its use today is so general that virtually every foundry making castings to high-strength requirements is familiar with the properties of molybdenum irons. It is estimated that about 15 percent of the current consumption of molybdenum is in cast iron.

ADDITION

In most instances the mechanical properties of cast iron can be improved by adding molybdenum without changing the normal melting practice. Ferromolybdenum can be added to the ladle, permitting only a part of the melt to be alloyed if so desired. Ferromolybdenum can also be added in the cupola, but very little is added in this fashion because of the solubility of reasonably high percentages of the crushed alloy in the ladle or at the spout.

Molybdic oxide briquets are used for direct addition to the cupola or furnace charge.

Molybdenum silicide can be added either to the ladle or at the cupola spout.

EFFECTS

The addition of molybdenum to gray iron increases tensile strength, transverse strength and deflection, and hardness and improves resistance to fatigue. Molybdenum, usually added in quantities of 0.25 to 1.25 percent, is one of the most effective elements added to gray iron to increase strength. The increase in strength of gray iron by adding molybdenum is attributed to a direct solid-solution effect in the ferrite, a refining action in the matrix, and an improvement in the size and distribution of the graphite.

According to Aufderhaar and Smith (*10*), increasing percentages of molybdenum decrease machinability; but hardness increases more rapidly than machinability decreases, and machinability does not become notably difficult until the molybdenum content reaches 1.5 percent, which point also marks maximum strength.

Molybdenum in cast iron is generally used in combination with other alloying elements. Some alloying combinations are; Chromium-molybdenum, nickel-molybdenum, nickel-chromium-molybdenum, molybdenum-vanadium, copper-molybdenum, and copper-chromium-molybdenum.

The largest consumer of molybdenum-bearing cast irons is probably the automotive industry, where they are used for dies, cylinder blocks, cylinder heads, bushings, and various other end products. The aircraft, machine-tool, railroad, and marine industries are also large consumers of molybdenum-bearing cast irons.

MOLYBDENUM IN SPECIAL AND NONFERROUS ALLOYS

Molybdenum's high melting point, good high-temperature creep properties, and availability are factors that have made it one of the most promising base metals for developing heat-resistant and structural alloys capable of supporting useful loads at temperatures above 1,600° F. Although studies of molybdenum-base alloys have shown them to be superior to

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TABLE 15.—*Nominal composition of some heat-resisting alloys containing molybdenum*

Brand name of alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Ti	Al	Fe	Others
A-286	[1] 0.08	1.25	[1] 1.0	14.75	25.5	----	1.25	----	----	2.10	[1] 0.35	REM	V 0.25
Croloy 15-15 N	[1] .15	[1] 2.00	[1] .75	16.00	15.00	----	1.55	1.40	1.05	----	----	REM	[1] N .15
Discaloy 24	.04	1.38	1.00	13.5	26.2	----	3.9	----	----	1.61	.11	REM	----
Haynes alloy 88	.07	1.50	.50	12.5	15.0	----	2.0	.6	----	.6	----	REM	B .15
S-588	.42	1.5	.8	18.4	20.0	----	4.0	4.0	4.0	----	----	REM	----
Timken 16-25-6	.10	1.35	.7	16.0	25.0	----	6.0	----	----	----	----	REM	N .15
19-9 DL	.30	1.10	.6	19.0	9.0	----	1.25	1.2	.4	.3	----	REM	----
19-9 DX	.30	1.00	.55	19.2	9.0	----	1.50	1.2	----	.55	----	REM	----
N-155	.15	1.5	.5	21.0	20.0	20.0	3.00	2.5	1.0	----	----	REM	N .15
Refractaloy 26	.05	.7	.7	18.0	37.0	20.0	3.00	----	----	2.8	.2	18.0	----
Refractaloy 80	.10	.6	.7	20.0	20.0	30.0	10.0	5.0	----	----	----	14.0	----
S-590	.42	1.25	.4	20.5	20.0	20.0	4.0	4.0	4.0	----	----	24.0	----
S-816	.38	1.20	.4	20.0	20.0	43.0	4.0	4.0	4.0	----	----	[1] 4.0	----
V-36	.31	.9	.5	25.0	20.0	42.0	4.0	2.6	2.2	----	----	3.0	----
Hastelloy alloy X	.15	----	----	22.0	45.0	----	9.0	----	----	----	----	REM	----
INCO 700	.10	.05	.2	15.0	49.0	28.0	3.0	----	----	2.0	3.0	.5	----
M-252	.15	1.0	.65	19.0	REM	10.0	10.0	----	----	2.5	.87	[1] 5.0	----
Waspaloy	[1] .10	[1] 1.0	[1] .75	19.5	REM	13.5	4.25	----	----	2.5	1.25	[1] 2.0	----
Hastelloy alloy B	.10	.8	.7	1.0	65.0	----	28.0	----	----	----	----	5.0	----
Hastelloy alloy C	.10	.8	.7	16.0	57.0	----	17.0	4.0	----	----	----	5.0	----
Haynes alloy 21	.25	.6	.6	27.0	3.0	62.0	5.0	----	----	----	----	1.0	----
Haynes alloy 30 (422-19)	.40	.6	.6	24.0	17.0	51.0	6.0	----	----	----	----	1.0	----

[1] Maximum.

the pure metal, oxidation in air at temperatures above 1,000° F. is probably their greatest weakness. The elements aluminum, chromium, columbium, silicon, titanium, tungsten, and vanadium are effective additions for improving the strength of molybdenum at both room and elevated temperatures.

Research indicates that the high-strength properties of molybdenum-base alloys, when properly protected from oxidation, are superior to those of other alloys at temperatures above 1,600° F. Although molybdenum-base alloys have been the subject of considerable research during the past few years and progress has been made in developing protective coatings and in fabrication of the alloys, they have not as yet been commercially produced for applications in air at high temperatures. Consequently, the major use of molybdenum in nonferrous and special alloys is restricted to relatively low percentages.

Commercially produced, molybdenum-bearing alloys include cobalt-base, iron-base, nickel-base, and tungsten-base, as well as powder-metallurgy compositions containing silver and copper. These alloys are used in a wide range of applications where the versatility of molybdenum as an alloying element is well known for its contribution to hardness, elevated-temperature strength, corrosion resistance, resistivity, or some other desired property, depending upon the base alloy.

Molybdenum in hard surfacing alloys contributes to hardness and improves resistance to heat, impact, and friction.

In nickel-iron alloys, for high magnetic permeability at low field strengths, molybdenum decreases sensitivity to cooling rate and increases resistivity.

Tungsten-molybdenum alloys are used as hooks in high-wattage lamps, supports and springs in discharge tubes, and heaters in radio tubes, as well as resistance wire in high-temperature electric furnaces.

Powder-metallurgy compositions containing molybdenum, silver, and copper are used for manufacturing electrical contacts. The good thermal and electrical conductivity of silver and copper, combined with the high hardness and density of molybdenum, are utilized, even though the metals do not form true alloys.

Many corrosion- and heat-resistant alloys contain molybdenum for its contribution to hardness, elevated-temperature strength, or some other property. These alloys probably account for the greater amount of molybdenum consumed in nonferrous and special alloys. The nominal composition of some of the heat-resistant alloys containing molybdenum is given in table 15.

MOLYBDENUM IN CHEMICALS

The addition of molybdenum to colors was probably its earliest commercial use, and only in recent years has it been widely employed in other chemical applications. Although the volume consumed for these purposes is small, they are important and increasing. The present chemical uses of molybdenum include the following:

REAGENTS

Molybdenum reagents are employed in a wide variety of laboratory analyses and tests, but the most important is the use of molybdic acid in phosphate determinations. Molybdic acid and molybdic anhydride constitute the major volume of molybdenum reagents consumed by the various laboratories, and because only minute quantities are consumed in individual analyses and tests, the total is very small.

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COLORS

According to Killeffer and Linz (*22*), applications of molybdenum compounds concerned with color divide themselves into four categories: (1) Molybdates used as pigments; (2) colored compounds of molybdenum formed in and on animal fibers in the manner and with the effect of a dye; (3) color lakes precipitated as insoluble compounds of dyes with phosphomolybdic acid; and (4) molybdenum compounds, mordant dyes to fibers.

Molybdenum orange is typical of the pigments, for it is formed by coprecipitation of the chromate and molybdate of lead The reaction of soluble molybdates with certain types of organic compounds is used to form the colors in and on animal fibers, while the colors of the dyes used to make lakes and mordant dyes are scarcely modified by combination of the dye with the molybdenum compound.

According to Climax Molybdenum Co. 1954 Annual Report to the Stockholders—

> Molybdenum orange is the leading pigment in its color range and is widely used in color blends from reds to light oranges. Consumption of molybdenum in pigments in 1954 was nearly 800,000 pounds, which was the highest on record.

CERAMICS

Molybdenum compounds are used in the ceramic industry for manufacturing white pigments and in conjunction with other elements to promote adherence of vitreous enamels to iron and steel.

CATALYSTS

Larger uses of molybdenum in chemicals include the manufacture of catalysts for oxidation-reduction reactions. The petroleum industry is among the largest, if not the largest, user of molybdenum catalysts. The demand for higher octane gasoline has brought about development of new catalytic refining processes, where molybdenum is one of the preferred catalytic materials because molybdenum catalysts are resistant to sulfur and other poisons.

Molybdenum catalysts are also employed in numerous other oxidation-reduction processes, such as the catalytic production of alcohols, formaldehyde, and petroleum-base chemicals.

Numerous patents covering a wide variety of uses have been issued on catalysts containing molybdenum. Killeffer and Linz (*57*) reviewed the patents on molybdenum catalysts and gave brief abstracts of some 1,755 patents, both United States and foreign, arranged in numerical order under the names of the countries granting them, and about 535 abstracts of journal articles.

According to Danziger and Kline (*77*), the expansion of re-forming and desulfurizing processes in the petroleum industry made catalysts the second largest market for molybdenum chemicals in 1954.

LUBRICANTS

An early use of molybdenite was for lubrication. At the beginning of the 19th century, the crude molybdenite from the Knaben mine, in the Knaben-Flekkefjord district, southern Norway, was used, under the names of "silver stone" and "lead-pencil stone" (*7*), by workmen to rub on their tools, but the use of purified molybdenite for modern lubrication is a development since World War II.

Molybdenite (MoS_2) is a blue-gray powder. It has a laminous molecular structure that is reported to be the basis for its lubricity. According to a manufacturer, many experts think that the layer of sulfur atoms adheres tightly to metals upon contact because the sulfur has a strong affinity for them, while the bond between the two adjacent layers of sulfur atoms is weak, permitting easy slippage over each other.

The lubricating action of dry molybdenum disulfide is said to be satisfactory over the temperature range extending from −40° to about 700° F., but because, in air, oxidation occurs above about 750° F., its use above 700° F. is restricted to nonoxidizing conditions.

Molybdenite is purified for use as a lubricant by refloating the concentrate and then treating at about 600° C. with either anhydrous hydrofluoric acid or sodium bifluoride to decompose silicates and volatilize their silica content, after which the product is washed free from soluble solids and dried in vacuum.

Molybdenum disulfide lubricants are manufactured in greases, oil dispersions, resin-bonded films, and dry powder. They are being used by most industrial countries. Annual consumption has grown from almost nothing a few years ago to approximately 300,000 pounds of contained molybdenum in 1955.

AGRICULTURE

Molybdic oxide and sodium molybdate are used to replace molybdenum deficiencies in certain soils. Australia and New Zealand have made large-scale tests on pasture lands, and in Florida citrus trees are sprayed with sodium molybdate to prevent the deficiency disease known as yellowspot.

OTHER

Molybdenum compounds are used in medicine and for other purposes, but the volume consumed is negligible compared with the major uses.

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SUBSTITUTES AND ALTERNATES

Because of the supply position of molybdenum and its versatility as an alloying element, there has been little substitution or replacement of molybdenum by other alloying elements. About the only substitution has been the use of boron in certain steels. These steels were used to a limited extent to replace steels containing molybdenum for its contribution to hardenability. Other possible means of substituting or using alternates for conserving molybdenum are to revert back to tungsten in certain high-speed and other tool steels and to the more extensive use of nickel, chromium, and vanadium in certain low-alloy steels. However, in view of the foreseeable supply relationship of the elements during an emergency, such a conservation measure does not appear to be justified. This would also apply to other possible conservation measures, such as replacement of molybdenum in manufacturing certain catalysts and orange pigments.

Probably the first use of molybdenum as a substitute for other materials was during World War I (1914–18), when it was reported to have been widely used by European countries to partly replace tungsten in certain high-speed steels. However, the degree of substitution is uncertain. During both World War II (1940–46) and the Korean War (1950–53) molybdenum replaced tungsten to a large extent in certain high-speed and other tool steels. This replacement was due primarily to the more favorable supply position of molybdenum.

National Emergency low-alloy steels developed in the early 1940's contained molybdenum in quantities from about 0.05 to about 0.40 percent. By the addition of molybdenum to these steels, the more critical supply elements (nickel, chromium, vanadium, etc.) were reduced in quantity. However, figures on the amounts of these elements conserved by the development and use of these steels are not available.

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WORLD TRADE

Significant world trade in molybdenum began just before World War I, when it is said that Germany started stockpiling the concentrate in anticipation of a shortage of tungsten. By the end of 1914 the price of 90-percent concentrate had skyrocketed. The shortage became so acute by the summer of 1917 that the British Government entered into contracts with producers for purchasing the entire Norwegian mine output during the remainder of that year and obtained an option from January 1, 1918, on all molybdenite produced in that country (7). However, this strong demand was short lived, for after the close of the war in 1918, world trade in molybdenum broke sharply and did not again become significant until peacetime applications were developed for the metal.

United States export data for molybdenum are not available for 1930–39, but it is reported that Climax Molybdenum Co. alone exported about 83 million pounds of molybdenum contained in concentrate during that period.

Molybdenum enters world trade in the form of a concentrate and in the form of various primary products; the most important include molybdic oxide, calcium molybdate, ferromolybdenum, and metal. The concentrate is normally traded in terms of contained molybdenum sulfide (MoS_2), but toward the end of 1954 price quotations in the United States were changed to contained molybdenum in concentrate grading 90 percent or more MoS_2. Pounds are the standard unit of weight in the United States, Canada, and the United Kingdom, but in Latin America and Europe kilograms or metric tons are used.

The United States, as the world's major source of molybdenum, has set the price pattern since about 1925. Before that time prices varied widely and hit a record high during World War I. Since 1925 the price of molybdenum has remained rather constant, increasing from a low of 35 cents per pound of molybdenite in 1930 to $1.10 per pound of molybdenum contained in concentrate at the end of 1955.

Under the Tariff Act of 1922, a duty of 35 cents per pound of molybdenum contained in ore or concentrate was imposed on imports of foreign ores and concentrates, and except for 1943–50, when (under terms of a trade agreement with Mexico) the duty was reduced to 17½ cents per pound, the duty remained the same.

EXPORTS

The four major exporters of molybdenum concentrate, arranged in order of importance, are the United States, Chile, Norway, and Canada. In previous years Australia and Mexico were important exporters of molybdenum, but production has virtually ceased in those countries. The United States is by far the world's leading exporter of molybdenum, normally more than the known production in the rest of the world. Chile and Norway export mostly to Europe, and much of Canada's production has been shipped to the United States for conversion and reshipment.

UNITED STATES

Following reopening of the Climax mine in 1924 the United States soon became the major exporting country, and by 1940—the first year for which statistics are available—more than 6.5 million pounds of molybdenum contained in concentrate was shipped, mainly to Canada and Europe. Table 16 gives the United States exports of molybdenum ore and concentrate for 1940–55, by countries of destination.

The United States is also a large exporter of molybdenum primary products, but statistics on some of the products are not separately recorded. United States exports of ferromolybdenum for 1942–55, by countries of destination, are given in table 17.

Several American firms, including the following, export molybdenum concentrate:

1. Climax Molybdenum Co.,
   500 Fifth Avenue,
   New York 36, N. Y.
2. Continental Ore Corp.,
   500 Fifth Avenue,
   New York 36, N. Y.
3. Bagdad Copper Corp.,
   Bagdad, Ariz.
4. Kennecott Sales Corp.,
   161 East 42d Street,
   New York 17, N. Y.
5. Metallurg, Inc.,
   100 Park Avenue,
   New York 17, N, Y.
6. Philipp Bros. Metal Corp.,
   70 Pine Street,
   New York 5, N. Y.
7. Union Carbide Nuclear Co.,
   Division of Union Carbide Carbon Corp.,
   30 East 42 Street,
   New York 17, N. Y.

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TABLE 16.—*Molybdenum ore and concentrate (including roasted concentrate) exported from the United States, by countries of destination, 1940–55, in pounds of contained molybdenum*

Country	1940	1941	1942	1943	1944	1945	1946	1947
Argentina								2, 050
Australia				103, 208				
Austria								6, 589
Belgium-Luxembourg								
Brazil	201, 362							
Canada	284, 458	500, 402	1, 006, 495	843, 500	853, 906	705, 633	30, 000	101, 650
Canal Zone								
Chile		15, 000						
Cuba							1, 940	
Czechoslovakia								21, 820
Denmark								
Finland								
France	2, 740, 065					354, 142		555, 840
Germany [1]								
India and Dependencies				20, 900				
Italy	849, 578							392, 378
Japan	117, 100							
Mexico	125							
Netherlands	6, 474					12, 544		
New Zealand								
Norway								
Southern Rhodesia				300				
Spain								
Sweden	29, 462					115, 364	301, 031	105, 915
Switzerland								
Taiwan								
Trieste								
United Kingdom	2, 019, 801	4, 757, 436	4, 482, 932	4, 992, 850	1, 110, 489		231, 153	1,803,009
U. S. S. R.	336, 289	2, 367, 492	6, 107, 213	4, 110, 399	4, 021, 005	1, 674, 834		
Venezuela							800	
Total	6, 584, 714	7, 640, 330	11, 596, 640	10, 071, 157	5, 985, 400	2, 862, 517	564, 924	2,989,251

Country	1948	1949	1950	1951	1952	1953	1954	1955
Argentina								
Australia					59, 085	1, 100		
Austria	10, 000	5, 334	20, 918	9, 996	34, 965	80, 020	305, 588	585, 405
Belgium-Luxembourg					23, 154	13, 400	15, 480	1, 998
Brazil								
Canada	159, 230	62, 289	226, 297	294, 687	535, 800	404, 626	232, 287	529, 359
Canal Zone			465	700	450	590		
Chile								
Cuba								
Czechoslovakia								
Denmark					3, 000			
Finland				2, 957	4, 400			
France	1, 591, 210	1, 525, 564	674, 296	420, 161	1, 735, 176	1, 368, 112	2, 306, 383	2, 368, 726
Germany [1]	131, 060	267, 285	1, 105, 577	761, 731	1, 986, 670	1, 028, 275	3, 725, 351	3, 621, 486
India and Dependencies								
Italy	63, 201	64, 906	43, 420	135, 712	192, 994	7, 056	145, 860	157, 324
Japan			40, 677	62, 340	199, 035	366, 547	540, 661	277, 196
Mexico		5, 370	345		12, 622	3, 119	2, 716	1, 000
Netherlands	13, 384	14, 700	61, 200	41, 524		4, 410	710, 945	217, 900
New Zealand					10, 080			
Norway		60, 000						
Southern Rhodesia							4, 000	
Spain					9, 990			
Sweden	262, 570	545, 761	274, 406	241, 349	479, 680	339, 208	806, 247	1, 465, 222
Switzerland					2, 476	595		
Taiwan						350		
Trieste							33, 919	
United Kingdom	1, 901, 686	2, 768, 571	3, 786, 920	1, 758, 108	882, 355	3, 420, 028	4, 717, 073	5, 354, 342
U. S. S. R.								
Venezuela								
Total	4, 132, 341	5, 319, 780	6, 234, 521	3, 729, 265	6, 171, 932	7, 037, 436	13, 546, 510	14, 580, 358

[1] West Germany.

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TABLE 17.—*United States exports of ferromolybdenum, by countries of destination, 1942–55, in pounds (gross weight)*[1]

	1942	1943	1944	1945	1946	1947	1948
Argentina					2, 252	8, 360	
Australia	478, 525	363, 400					
Austria							11, 200
Belgian Congo		220					
Belgium-Luxembourg					23, 138	78, 274	64, 841
Bolivia					500	221	2, 000
Brazil		21, 280	13, 115	2, 200		1, 000	2, 400
Canada	363, 638	285, 326	340, 005	375, 770	97, 889	105, 190	207, 193
Canal Zone					1, 469		
Chile	200	1, 440	700	700	3, 082		
China	40, 000		500	2, 200	16, 078		6, 188
Colombia							100
Cuba		200					
Czechoslovakia					77, 000	33, 500	
Denmark							20, 750
Finland						20, 904	
Germany						112, 000	592, 400
Greece						200	300
India	1, 601, 571						11, 000
Italy					159, 000	67, 200	92, 115
Japan							
Mexico		218	440		4, 100	7, 295	7, 782
Netherlands						11, 030	53, 812
Netherland Antilles		400	949				1, 000
New Zealand	250	400	2, 200	3, 300	1, 100	100	
Norway							11, 000
Palestine and Trans-Jordan			1, 772				
Peru			400	1, 600		500	
Poland and Danzig					33, 000		
Portugal					4, 502	2, 240	17, 920
Spain					17, 493		
Sweden				11, 408	299, 600	503, 820	
Switzerland				15, 409	220	1, 200	68, 788
Taiwan							
Thailand							
Turkey	35, 897	33, 500					
United Kingdom	3, 569, 872	333, 760		55, 115			
Union of South Africa		75, 000	10, 000		100		17, 719
U. S. S. R.			4, 057, 500	1, 300, 000			
Uruguay		700					441
Venezuela							
Yugoslavia							
Total	6, 089, 953	1, 115, 844	4, 427, 581	1, 767, 702	740, 523	953, 034	1, 188, 949

[1] Average ferromolybdenum contains 60–66 percent molybdenum.

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TABLE 17.—*United States exports of ferromolybdenum, by countries of destination, 1942–55, in pounds (gross weight)* [1]—Continued

	1949	1950	1951	1952	1953	1954	1955
Argentina						2, 095	6, 350
Australia			67, 734	51, 826			
Austria	146, 200	131, 000	248, 816	81, 239	65, 044		
Belgian Congo		2, 240	16, 530	16, 429	21, 406		
Belgium-Luxembourg	76, 914	173, 272	120, 708	159, 960	41, 407	12, 682	
Bolivia					1, 100		2, 000
Brazil	3, 923	5, 500	22, 524	7, 213	7, 750	24, 564	14, 212
Canada	143, 200	250, 550	315, 394	439, 476	201, 626	79, 856	174, 504
Canal Zone							
Chile	1, 101	550	4, 347	7, 825		1, 770	1, 100
China	4, 380						
Colombia					900		
Cuba							
Czechoslovakia							
Denmark	50, 340	4, 600	10, 847	12, 639	6, 178		
Finland	13, 440	5, 600	32, 121	32, 296	22, 776		25, 959
Germany							
Greece							
India				200			
Italy	35, 704	367, 595	136, 042	65, 613	106, 277	4, 408	11, 000
Japan		190, 000	369, 016	23, 982	88, 060		
Mexico	300	3, 000		2, 862	6, 623	2, 450	11, 530
Netherlands	82, 269	11, 652	35, 037	22, 154			
Netherland Antilles							
New Zealand	200					1, 000	
Norway	11, 200	11, 200	28, 120	3, 211			
Palestine and Trans-Jordan							
Peru							
Poland and Danzig							
Portugal	2, 240		1, 940	2, 894			
Spain		551	37, 051	37, 531	45, 974	40, 316	
Sweden	24, 293	11, 000	13, 706				10, 000
Switzerland	98, 444	1, 210	4, 208	36, 097			
Taiwan		200		839	1, 000		1, 200
Thailand				250			
Turkey			200	8, 198	25, 304	2, 622	
United Kingdom							
Union of South Africa	260, 955	8, 974	14, 500	37, 298	4, 886	76, 000	67, 200
U. S. S. R.							
Uruguay							
Venezuela			5, 000				
Yugoslavia				40, 072			24, 138
Total	955, 103	1, 178, 604	1, 483, 841	1, 090, 104	646, 411	247, 763	349, 193

[1] Average ferromolybdenum contains 60–66 percent molybdenum.

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TABLE 18.—*Molybdenum concentrate exported from Chile, by countries of destination, 1939–55, in metric tons (gross weight)*[1]

[Division of Foreign Activities Bureau of Mines]

Year	Belgium	France	Germany	Italy	Japan	Netherlands	Norway	Sweden	United Kingdom	United States	U.S.S.R.	Total
1939									42			42
1940					679		26					705
1941										336		336
1942										1,095		1,095
1943										1,284		1,284
1944										1,825		1,825
1945									419	203		622
1946		1,185						451	433		255	2,324
1947		227						74	455			756
1948								52	1,123			1,175
1949	42							246				288
1950		328	865	53				501	385			2,132
1951		725	358					141	2,200	700		4,124
1952		607		30				134	2,631			3,402
1953		209	350			307		67	1,624			2,557
1954		203	216			242		86	1,759			2,506
1955		208	181			234		150	1,798			2,571

[1] Normally 96 percent MoS_2.

TABLE 19.—*Molybdenum ore and concentrate exported from Norway, by countries of destination, 1935–54, in pounds (gross weight)*

Year	Austria	Belgium-Luxembourg	Czechoslovakia	France	Germany	Italy	Japan and Korea	Netherlands	Poland and Danzig	Sweden	United Kingdom	U.S.S.R.	Other	Total
1935	288	68,904		358,793	237,226	11,348	117,852			398,845	186,868			1,380,124
1936		71,940		106,124	798,094					266,488	396,748		213	1,639,607
1937					737,926				880	411,741	196,680			1,347,227
1938		12,430	286		913,526					824,313				1,750,555
1939				34,760	913,710					446,046	93,192			1,487,708
1940					553,518					678,286				1,231,804
1941					584,019					292,987			110	877,116
1942					932,589					466,055				1,398,644
1943					651,503					304,124				955,627
1944					867,154					10,756				877,910
1945					371,263					197,025				568,288
1946										22,106				22,106
1947										155,863		226,367		382,230
1948												290,563		290,563
1949												194,654		194,654
1950													110	110
1951	21,518							93,623		580,514	22,315		55	718,025
1952	16,392									485,142	46,924		1,269	549,727
1953										447,412	93,773			541,185
1954						11,724				630,667	55,814			698,205

FOREIGN COUNTRIES

CHILE

Chile, the world's second largest exporter of molybdenum ore and concentrate, ships mostly to Europe, but during World War II the United States obtained most of its output. Molybdenum ore and concentrate exported from Chile for 1939–55, by countries of destination, are given in table 18.

NORWAY

Norway has been almost a continuous exporter of molybdenum ore and concentrate since before the beginning of the century. Norway's exports of ore and concentrate for 1935–54, by countries of destination, are given in table 19.

OTHER

Korea, Finland, French Morocco, and Peru have exported appreciable quantities of molyb-

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denum ore and concentrate; but in recent years Finland and French Morocco have had no output, and exports from Korea and Peru have been exceedingly small.

IMPORTS

MAJOR IMPORTING COUNTRIES

The major molybdenum-ore and concentrate importing countries in 1955, arranged in alphabetical order, were Austria, France, Germany (West), Italy, Japan, Sweden, and the United Kingdom. United States imports have been minor and are given, by countries of origin, for 1940–55 in table 20. Import statistics for other countries are not available in terms of contained molybdenum. During World War II, the U. S. S. R. imported large quantities of molybdenum from the United States.

TABLE 20.—*United States imports of molybdenum ore and concentrates by countries of origin, 1940–55, in thousand pounds of contained molybdenum*

Year	Canada	Chile	Mexico	Peru	Other countries	Total
1940						
1941					4	4
1942	1	755				756
1943	[1] 216	1,406	11	156		1,789
1944	[1] 1,145	2,165	22	167		3,499
1945	[1] 461	138		66		665
1946		[1] 276				276
1947						
1948						
1949					48	48
1950					3	3
1951	8					8
1952	50					50
1953						
1954	154					154
1955	134					134

[1] Imports for conversion and reexport.

Import statistics for primary molybdenum products are not available, except for the United States; even for this country imports are negligible.

Some European firms known to import molybdenum concentrate or primary products from the United States follow:

Austria

1. Gebr. Boehler,
   Kapfenberg, Styria, Austria.
2. Metallwerke Plansee,
   Reutte, Tyrol, Austria.

England

3. Climax Molybdenum Co., of Europe, Ltd.,
   2 and 3 Crosby Square,
   London E. C. 3, England.
4. Ferroalloys & Metals, Ltd.,
   Glossop, Derbyshire, England.
5. Minworth Metals, Ltd.,
   Birmingham, England.
6. Murex, Ltd.,
   Rainham, Essex, England.

France

7. Soc. Commerciale de Minéral de Molybdène et de Ferro-Molybdène,
   11 Rue Portalis,
   Paris 8, France.

Germany

8. Badische Wolframerz-Gesellschaft m. b. H.
   Söllingen/kr,
   Karlsruhe,
   Baden, Germany.
9. E. Merck,
   Darmstadt, Germany.
10. Hermon C. Starck,
    Gosler, Germany.
11. Horbach & Schmitz,
    Neusser Strasse 26,
    Cologne, Germany.

Italy

12. Soc. P. Azioni Leghe e Metalli,
    Via Cairoli 2–7,
    Genoa, Italy.

Netherlands

13. Phillips,
    Eindhoven, Netherlands.

Sweden

14. Aktiebolaget Ferrolegeringar,
    Trollhatten, Sweden.
15. Gullspongs Elektrokeniski Aktiebolay,
    Gullspongs, Sweden.

INTERNATIONAL MATERIALS CONFERENCE

The heavy world demand for molybdenum and other strategic commodities brought about by the Korean War greatly exceeded supply. To assure equitable distribution, the United States, France, and the United Kingdom sponsored the organization of the International Materials Conference.

The organization scheduled its first meeting for March 8, 1951, with Australia, Bolivia, Brazil, Canada, Federal Republic of Germany, France, Spain, Sweden, United Kingdom, and the United States accepting invitations. By the third quarter of the same year the Tungsten and Molybdenum Committee had issued allotments covering distribution of molybdenum which had been approved by governments of the

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TABLE 21.—*Distribution of molybdenum ore and concentrate and primary products by International Materials Conference, in metric tons of molybdenum content*

Country	Summary, last half of 1951 [1]			Summary in 1952 [2]			Summary, first half of 1953 [3]		
	Distribution of ore and concentrate	Export of primary products [4]	Distribution of primary products [4]	Distribution of ore and concentrate	Export of primary products	Distribution of primary products	Distribution of ore and concentrate	Export of primary products [5]	Distribution of primary products
Argentina						0. 525			0. 4
Australia			14			85. 0			51. 0
Austria			21	17. 5		76. 5	8. 0		31. 5
Belgium			16			96. 0			50. 0
Brazil			8			20. 2			2. 0
Canada			48			375. 5			220. 0
Chile				1. 0		3. 0	. 5		1. 5
Denmark						6. 0			4. 0
Egypt									. 2
Finland						10. 0			7. 0
Formosa						. 5			1. 0
France	427	25		1, 217. 0	165. 5		660. 0	40	
Germany	282	1		972. 95	79. 45		666. 0	21	
India						4. 0			4. 0
Italy	20		10	78. 5		104. 0	30. 0		69. 0
Japan	40			225. 0			86. 0		
Mexico						0. 85			3. 5
Netherlands	5		5	17. 0		16. 5			10. 0
New Zealand						12. 375			7. 4
Norway						11. 0			8. 0
Portugal			2			8. 0			4. 0
Saudi Arabia									1. 0
South Africa			5			22. 5			14. 0
Spain			7			33. 5			22. 0
Sweden	206	13		468. 0	58. 5	12. 0	250. 0	17	6. 0
Switzerland			12	4. 0		49. 0	2. 0		12. 0
Turkey						9. 5			3. 5
United Kingdom	1, 053	25		2, 215. 5	137. 5		1, 000. 0	40	
United States	7, 040	90		16, 121. 6	527. 0		9, 900. 0	166	
Yugoslavia			4			10. 5			9. 0
Reserve	47		2	7. 95					
Total	9, 120	154	154	21, 346. 00	967. 95	966. 950	12, 602. 5	284	542. 0

[1] Mineral Trade Notes, vol. 33, No. 5, November 1951.
[2] Tungsten-Molybdenum Committee Doc. Nos. 102 (rev.), Mar. 25, 1952; 120 (Rev. 2) July 10, 1952; and 136, Nov. 17, 1952.
[3] Tungsten-Molybdenum Committee Doc. Nos. 144, Dec. 16, 1952, and 155, Mar. 20, 1953.
[4] 4th quarter of 1951.
[5] 1st quarter of 1953.

NOTE.—Quantities shown under ore and concentrate are the net quantities for domestic use. Primary products include ferromolybdenum, molybdic acid, and molybdenum salts, including calcium molybdate and molybdic oxide.

member nations. The first allotments, which were for the third quarter of 1951, were for molybdenum in concentrate. No specific provision for primary products was made, other than that it was agreed that normal shipments, for export, of primary products would be continued by participating nations. However, following the initial allocation, special allotments were made for molybdenum to be exported as primary products.

The International Materials Conference released molybdenum from allocation on June 11, 1953. Distribution of molybdenum ore and concentrate and of primary products is given, by countries, in table 21.

International Materials Conference export and import quotas for molybdenum ore and concentrate are given in table 22.

UNITED STATES TARIFFS

United States import duties on molybdenum levied by Tariff Acts and Trade Agreements follow:

TARIFF ACT OF 1913

* * * Ferromolybdenum, molybdenum, * * * and other molybdenum alloys used in the manufacture of steel * * * 15 per centum ad valorem (par. 102); if unwrought metal 10 per centum ad valorem (par. 154).

* * * Chemical compounds (calcium molybdate and other molybdenum compounds) * * * 15 per centum ad valorem (par. 5).

TARIFF ACT OF 1922

* * * Molybdenum ore or concentrates, 35 cents per pound on the metallic molybdenum contained therein * * * ferromolybdenum, metallic molybdenum, molybdenum powder, calcium molybdate, and all other compounds and alloys of molybdenum, 50 cents per pound

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TABLE 22.—*International Materials Conference export and import quotas of molybdenum ore and concentrate, in metric tons of metal content*

Country	3d qtr., 1951 [1]	4th qtr., 1951 [1]	1st half, 1952 [2]	3d qtr., 1952 [3]	4th qtr., 1952 [4]	1st qtr., 1953 [5]	2d qtr., 1953 [5]
Exports							
Canada			50	25	25	15	35
Chile	275	365	1,026	750	408.5	410	370
Korea			10	30			
Norway	25	30	80	43.5	45.5	40	44
Peru				1.5	1.5	2	2
United States	680	680	1,237.5	534.5	653.5	901	930
Yugoslavia						3	
Total	980	1,075	2,403.5	1,384.5	1,134	1,371	1,381
Imports							
Austria			4	5			
France	195	232	544	304	337	355	345
Germany	125	157	372.5	273	300	321	366
Italy		20	52.5	13	13	20	10
Japan		15	59	33			26
Netherlands		5	10	3.5	3.5		
Sweden	100	106	226.5	115.5	118	134	133
United Kingdom	515	538	1,134.5	631	360	540	500
Other countries	45		.5	2	2.5		
Reserve		2		4.5			
Switzerland						1	1
Total	980	1,075	2,403.5	1,384.5	1,134	1,371	1,381

[1] Mineral Trade Notes, vol. 33, No. 5, November 1951.
[2] IMC Tungsten-Molybdenum Committee Doc. 102 (rev.), Mar. 25, 1952.
[3] IMC Tungsten-Molybdenum Committee Doc. 120 (rev. 2), July 10, 1952.
[4] IMC Tungsten-Molybdenum Committee Doc. 136, Nov. 17, 1952.
[5] IMC Tungsten-Molybdenum Committee Doc. 144, Dec. 16, 1952.

on the molybdenum contained therein and 15 per centum ad valorem * * *(par. 302).

Steel: In addition to the rates of duty provided for in this schedule (Schedule 3: Metals and Manufacturers of) on steel in all forms and shapes * * * containing more than six-tenths of 1 per centum of * * * molybdenum * * * 8 per centum ad valorem * * * an additional cumulative duty of 65 cents per pound on the molybdenum content in excess of six-tenths of 1 per centum * * * (par. 305).

TARIFF ACT OF 1930

Molybdenum ore or concentrate, 35 cents per pound on the metallic molybdenum contained therein (par. 302b).

Ferromolybdenum, metallic molybdenum, molybdenum powder, calcium molybdate, and all other compounds and alloys of molybdenum, 50 cents per pound on the molybdenum contained therein and 15 per centum ad valorem (par. 302f).

Steel or iron which contains * * * more than two-tenths of 1 per centum of molybdenum * * * in addition to the rates of duty provided on similar forms of plain carbon steel and iron without alloys (as provided in various other paragraphs of the act), 8 per centum ad valorem * * * and a further cumulative duty of 65 cents per pound on the molybdenum content in excess of two-tenths of 1 per centum * * * (par. 305).

Ingots, shot, bars, sheets, wire, or other forms, not separately provided for, or scrap, containing more than 50 per centum tungsten, tungsten carbide, molybdenum, or molybdenum carbide or combinations thereof: Ingots, shot, bars or scrap, 50 per centum ad valorem; sheets, wire, or other forms, 60 per centum ad valorem (par. 316b).

Molybdenum orange 25 per centum ad valorem (par. 70).

TRADE AGREEMENTS

A trade agreement consummated with Mexico effective January 30, 1943, reduced the duty on molybdenum ore or concentrate to 17½ cents per pound of molybdenum contained therein. The trade agreement terminated on December 31, 1950, reverting the duty back to 35 cents per pound of molybdenum contained therein.

The General Agreement on Tariffs and Trade (Torquay), effective June 6, 1951, reduced the duty on ferromolybdenum, molybdenum metal and powder, calcium molybdate, and other compounds and alloys of molybdenum to 25 cents per pound of molybdenum contained therein and 7.5 per centum ad valorem.

Duty on steel or iron containing over two-tenths of 1 per centum of molybdenum, 4 per centum ad valorem and a further cumulative duty of 35 cents per pound of molybdenum in excess of two-tenths of 1 per centum contained therein.

At the end of 1955 tariff on molybdenum ore and concentrate remained at 35 cents per pound of contained molybdenum; that on ferromolyb-

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denum, molybdenum-metal powders, calcium molybdate, and other compounds and alloys of molybdenum was 25 cents per pound of contained molybdenum plus 7.5 percent ad valorem, except molybdenum orange, which was 12.5 percent ad valorem.

PRICES

At the beginning of the century, when the demand for molybdenum was very uncertain, no definite market prices were established. Even just before World War I the price varied from about 70 cents to $2 per pound of MoS_2 contained in concentrate grading about 90 percent or more MoS_2. This wide fluctuation apparently was due to heavy buying by Germany in preparation for the war.

Price developments during World War I, as summarized by the United States Tariff Commission (*6*), were as follows:

In September, 1915, the British Admiralty, which had commandeered the entire molybdenum output of British controlled territory soon after war had been declared, fixed its price at about $1.10 per pound for 90-percent material. This was a cut of 25 to 50 percent of the then prevailing prices. The sporadic demand that appeared in the United States in 1914 declined, but prices were then dominated by a strong European demand. By 1917, quotations for high-grade molybdenite were $1.80 a pound. A spectacular flurry drove the price to above $3 in May, but except for this one month, the year was marked by a steady rise with 90-percent molybdenite quoted at about $2.25 and in good demand in the last of the year. In 1918, the embargo on British molybdenum was lifted; and in February, the large output of concentrate from the new Colorado field came into the market, which slowly broke in successive reductions that brought the price down to $1 a pound in August. There was a very limited market in the year 1919, occasional quotations appearing at from 65 cents to 85 cents per pound.

Nominal prices for molybdenum concentrate, calcium molybdate, molybdic oxide, ferromolybdenum, and metal from 1920 to 1955 are given in table 23.

TABLE 23.—*Prices of molybdenum concentrate and products in the United States, 1920–55* [1]

Year	Concentrate per pound MoS_2	Calcium molybdate per pound contained Mo	Molybdic oxide per pound contained Mo	Ferromolybdenum per pound contained Mo	Molybdenum metal (powder)
1920	$0.55–$0.85	[2]	[2]	$2.25–$3.00	[2]
1921	.45– .60	[2]	[2]	2.00– 2.50	[2]
1922	.45– .80	[2]	[2]	2.00– 2.50	[2]
1923	.75– 1.05	[2]	[2]	1.90– 2.50	[2]
1924	.65– .80	[2]	[2]	1.80– 2.25	[2]
1925 [4]	.65– .70	[2]	[2]	1.25– 1.80	[2]
1926 [5]	.48– .70	$1.20	[2]	[2]	[2]
1927	.48– .50	1.20	[2]	1.25– 1.45	[2]
1928	[2]	.95	[2]	1.00– 1.25	[2]
1929	[2]	.95	[2]	1.20– 1.25	[2]
1930	.35– .50	.95	[2]	1.00– 1.20	[2]
1931	.35– .45	.85	[2]	1.00	$4.50–$7.00
1932	.42– .45	.85	[2]	.95– 1.00	4.50
1933	.45	.80– 0.85	[2]	.95	4.10– 4.50
1934	.45	.80– .85	[2]	.95	4.10
1935	.45	.80	[2]	.95	4.10
1936	.45	.80	[2]	.95	4.10
1937	.45	.80	[2]	.95	4.10
1938	.42– .45	.80	[2]	.95	2.60– 4.10
1939	.45	.80	[2]	.95	2.60– 3.00
1940	.45	.80	[2]	.95	2.60– 3.00
1941	.45	.80	[2]	.95	2.60– 3.00
1942	.45	.80	[2]	.95	2.60– 3.00
1943	.45	.80	$0.80	.95	2.60– 3.00
1944	.45	.80	.80	.95	2.60– 3.00
1945	.45	.80	.80	.95	2.60– 3.00
1946	.45	.80	.80	.95	2.60– 3.00
1947	.45	.80	.80	.95	2.60– 3.00
1948	.45	.80	.80	.95	2.60– 3.00
1949	.54	.96	.95	1.10	2.60– 3.00
1950	.54– .60	.96– 1.15	.94–$1.14	1.13– 1.32	2.60– 3.00
1951	.60	1.15	1.14	1.32	3.00
1952	.60	1.15	1.14	1.32	3.00
1953	.60	1.15	1.14	1.32	3.00
1954	[6] .60– 1.04	1.15– 1.28	1.14– 1.25	1.32– 1.49	3.00
1955	[6] 1.05– 1.10	1.28– 1.34	1.24– 1.31	1.46– 1.66	3.00

[1] Quotations for molybdenum concentrate, calcium molybdate, and ferromolybdenum for 1920–31 taken from Bureau of Mines Econ. Paper 15, Molybdenum, pp. 33–34; for 1932–54, Engineering and Mining Journal.
[2] Not quoted.
[3] Not available.
[4] Ferromolybdenum quotations, January to July only.
[5] Calcium molybdate quotations, August to December only.
[6] Beginning December 10, 1954, molybdenite-concentrate prices quoted were on contained molybdenum plus cost of containers.

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CONTROLS

The history of controls in the United States during World War II is given in "History of the War Production Board and Predecessor Agencies, 1940–45, Industrial Mobilization for War, 1947," by the former Civilian Production Administration, and in Federal Records of World War II, 1950, by General Services Administration. Control orders issued during World War II were issued by Economic Stabilization Agency, Office of Price Administration, Office of Production Management, and War Production Board. Since the close of World War II, control orders have been issued by National Production Authority and Office of International Trade and its successor agency, Bureau of Foreign Commerce.

DOMESTIC USE CONTROLS

WORLD WAR II

Office of Production Management, General Metals Order 1, issued May 1, 1941, provided that molybdenum could not be shipped to customers in quantities that would increase their inventories to unnecessary levels. Molybdenum was then placed on the Priorities Critical List, and the order was extended to October 15, 1941, and subsequently revoked.

General Preference Order M–14—High-Speed Steel, issued June 11, 1941, provided that a customer for high-speed steel could not purchase the tungsten-type steel (containing 12 percent or more tungsten) if the molybdenum-type (7.0 percent or less tungsten and 3 percent or more molybdenum) would serve as well. The order also provided that, during any 3-month period, beginning June 1, 1941, a customer for high-speed steel might purchase tungsten-type high-speed steel only to the extent that he bought molybdenum-type high-speed steel. The order was amended November 29, 1941, and again December 31, 1941. It was revoked December 14, 1942.

General Preference Order M–21—Iron and Steel, issued August 9, 1941, covered the distribution of steel and iron products. This basic M order was completely revised June 9, 1943, effective July 1, 1943. Paragraphs (g) through (i) were deleted May 8, 1944, and with amendments were redesignated (h) through (j) on the same date.

General Preference Supplementary Order M–21–a—Alloy Iron and Steel, directed the production and deliveries of alloy iron, alloy steel, and wrought iron and required melters to file a monthly melting schedule, except for tool steel, as defined by Supplementary Order M–21–b. The order was amended December 20, 1941, and May 11, 1942, and was revised completely December 14, 1942. The revised order was amended February 13, 1943, March 24, 1943, and December 1, 1943, and again revised January 21, 1944.

General Preference Supplementary Order M–21–b—Tool Steel, issued December 14, 1942, and amended April 22, 1943, required that 75 percent of all high-speed-steel orders accepted in any 1 quarter be of the molybdenum type and not more than 25 percent of the tungsten type; it was modified to permit a leeway of 5 percent by weight, or within 500 pounds, in meeting the ratio. The amendment of May 10, 1943, raised the permitted ratio of tungsten-type high-speed steel to 35 percent.

General Preference Supplementary Order M–21–j—Tool Steel, issued April 7, 1945, was amended May 18, 1945. It directed that, of all high-speed tool steel melted, delivered, or accepted, not over 15 percent should be class B (straight tungsten steel) and the balance should be class A (to contain 6.75 percent or less tungsten and 3 percent or more molybdenum). The order was revoked July 2, 1945.

General Preference Order M–110—Molybdenum, was issued March 18, 1942, to conserve the supply and control the distribution of molybdenum. The order provided for complete allocation of molybdenum in all forms, including scrap. It was completely revised December 30, 1943.

Supplementary Order M–110–a—Small Deliveries of Molybdenum, issued November 6, 1942, permitted, under certain conditions, deliveries up to 500 pounds of contained molybdenum in any 1 month without allocation. This order was revoked December 30, 1943.

General Preference Order M–369—Tungsten and Molybdenum Products, issued December 31, 1943, restricted the deliveries of tungsten and molybdenum products in pure form fabricated to the extent that it was hydrogen-reduced powder, ingot, wire, rod or sheet, or further fabricated into shapes such as, but not limited to, coils, filaments, spirals, grids, welds, leads or plates, but did not include molybdenum in the form of carbon-reduced powder or molybdenum contacts. The order was amended February 7, 1944, and revoked July 20, 1944.

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Civilian Production Administration Order M–21 authorized controls over alloy steel and ferrolloying materials. The order continued in force during 1946, but no active controls were instituted.

KOREAN WAR

NPA Order M–33, issued January 27, 1951, established specific inventory limitations for molybdenum in pure form as metal powder or in any shape into which it might be fabricated, and ferromolybdenum, molybdic oxide, calcium molybdate, and other combinations of molybdenum with other elements in semimanufactured or manufactured form, prepared for consumption in the manufacture of steel or for other purposes, and all primary chemical compounds having molybdenum as an essential and recognizable component.

NPA Order M–1, amended April 6, 1951, established procedures for virtually complete control over the use of ferroalloys in the production of alloy iron, steel, or nonferrous products.

NPA Orders M–80 and M–81, issued August 15, 1951, superseded NPA Orders M–1–18 (b) and M–33.

Order M–80—Iron and Steel—Alloying Materials and Alloy Products, required all melters and processors to file proposed melting or processing schedules and data concerning inventories. This order terminated June 30, 1953.

Order M–81—Pure Tungsten and Pure Molybdenum, applied only to carbon- and hydrogen-reduced, substantially pure tungsten and pure molybdenum. It made pure molybdenum subject to allocation and end-use restrictions and required the filing of monthly reports. This order was amended September 12, 1952, to eliminate the requirement that deliveries of pure tungsten and pure molybdenum be made pursuant to allocation authorizations only. This order was revoked April 16, 1953.

Defense Minerals Administration (later Defense Materials Procurement Agency) Order MO–8, issued June 8, 1951, provided for the allocation of molybdenum ore and concentrate for domestic shipments and for exports for foreign consumption. This order was amended February 13, 1953, to terminate domestic allocation, and the entire order was revoked August 11, 1953.

EXPORT CONTROLS

WORLD WAR II

On July 2, 1940, an act approved by Congress gave the President authority to prohibit or curtail the exportation of military equipment or munitions, materials, or supplies necessary for the manufacture, servicing, or operation thereof. On the same date the President issued a proclamation providing for individual licensing, among other articles and commodities, of molybdenum ore, concentrate, metal, alloys containing over 10 percent molybdenum, and molybdenum compounds. The responsibility for administering the program was vested in the Administrator of Export Control, who was designated by a military order, also dated July 2, 1940, and the United States Department of State. Later, by Executive orders, the functions of export control were transferred to Economic Defense Board, Board of Economic Warfare (by change of name), Office of Economic Warfare, and Foreign Economic Administration.

The individual licensing of molybdenum was carried out only after an Interdepartmental Foreign Requirements Committee had approved the essential requirements of the friendly countries and made recommendations for meeting those requirements, which were then submitted to the War Production Board for review and analysis by its Foreign Division, where lend-lease requisitions were also checked.

On July 9, 1942, an order issued by the Board of Economic Warfare permitted exportation of molybdenum ore, concentrate, products, alloys, and scrap to Canada and Newfoundland under general license.

KOREAN WAR

The United States defense program and mobilization effort, brought about by the outbreak of hostilities between North and South Korea in June 1950, quickly resulted in a growing shortage of most additive metals, including molybdenum. Before many months had passed, molybdenum was placed under total allocation.

With respect to exports, the United States Department of Commerce placed molybdenum ore and concentrate, metals and alloys in crude form (including scrap), ferromolybdenum, and molybdenum wire under short-supply export controls, effective January 1, 1951. For several quarters extremely restrictive quantitative quotas were in effect. By the third quarter of 1951, however, essential foreign requirements had been firmly fixed, and a quota of 1.6 million pounds established for molybdenum ores and concentrate, ferromolybdenum, and certain molybdates; a token quota was also established for molybdenum metal and alloys in crude form (including scrap), and molybdenum wire and filament. These quarterly export quotas continued in effect until first quarter of 1953, when the quota for ores, ferromolybdenum, etc., was increased to 2.1 million pounds.

Between the imposition of short-supply export controls on January 1, 1951, and first quarter of 1953, coverage of these controls was ex-

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panded to include molybdenum filaments and molybdates (3Q51), molybdenum semifabricated forms, welding rods, and powder (2Q52), and molybdenum chemical compounds (4Q52).

With conclusion of the fighting in Korea, the supply situation with respect to molybdenum soon improved enough to permit discontinuance of all domestic allocation controls. By the end of 1953 the situation was such as not to warrant continuation of restrictions over exports either, and on January 8, 1954, short-supply export controls on molybdenum were formally abandoned.

PRICE CONTROLS

WORLD WAR II

Office of Price Administration Maximum Price Regulation 489, issued November 8, 1943, froze the price of ferromolybdenum at 90 cents per pound of contained molybdenum, molybdic oxide (Technical grade), and calcium molybdate at 80 cents per pound of contained molybdenum. The maximum prices for molybdenum-metal powder, molybdenum carbide powder, molybdic acid, molybdenum trioxide, molybdenum silicide, sodium molybdate, ammonium molybdate, other molybdenum alloys, and compounds consumed principally by the metallurgical industry were fixed at the highest prices charged or quoted for such products by a seller on a delivery made during January, February, or March 1942 to a purchaser of the same class. Molybdenum ore and concentrate were not subject to the regulations. The regulations were revoked June 12, 1946.

KOREAN WAR

Economic Stabilization Agency General Ceiling Price Regulations, issued January 26, 1951, froze the prices of virtually all commodities, including molybdenum, at the highest price received during the period December 19, 1950, to January 25, 1951.

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